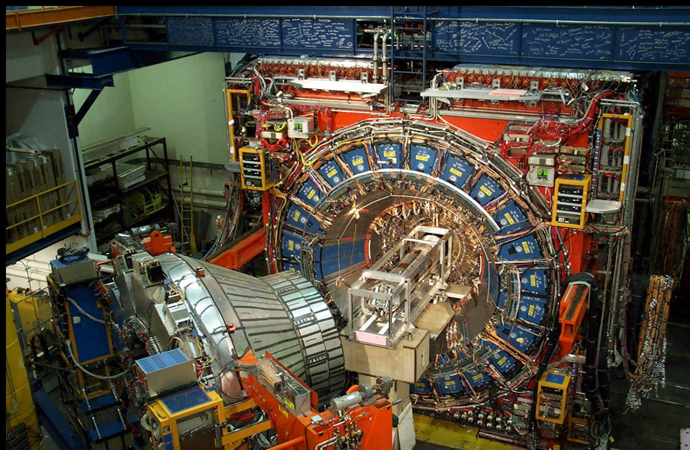
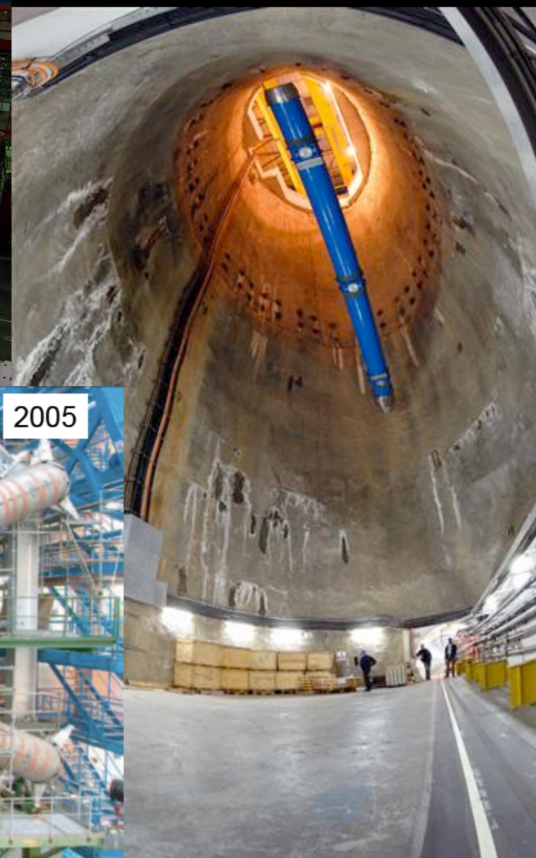
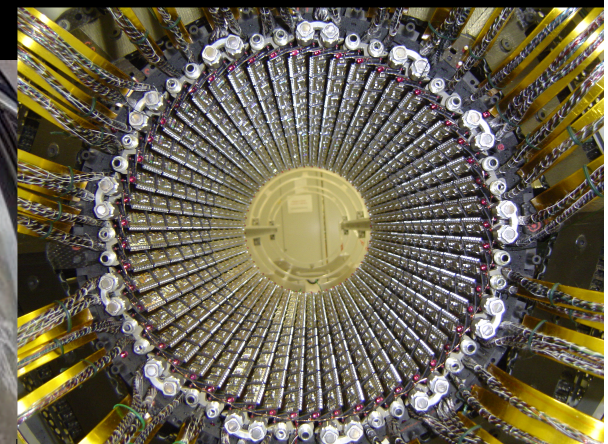
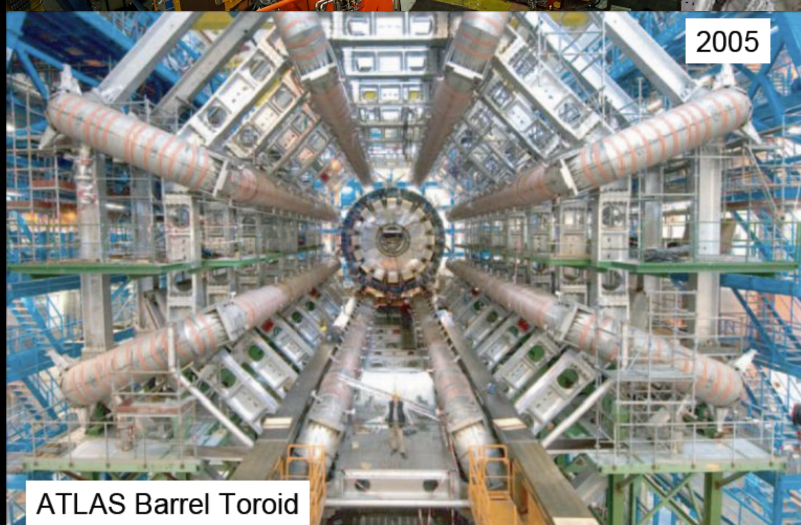
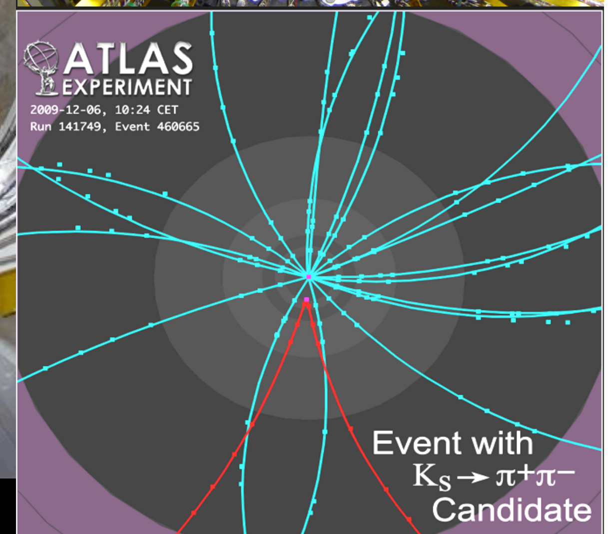
Particle Physics from Tevatron to LHC: what we know and what we hope to discover











Beate Heinemann, UC Berkeley and LBNL

DESY, March 2010

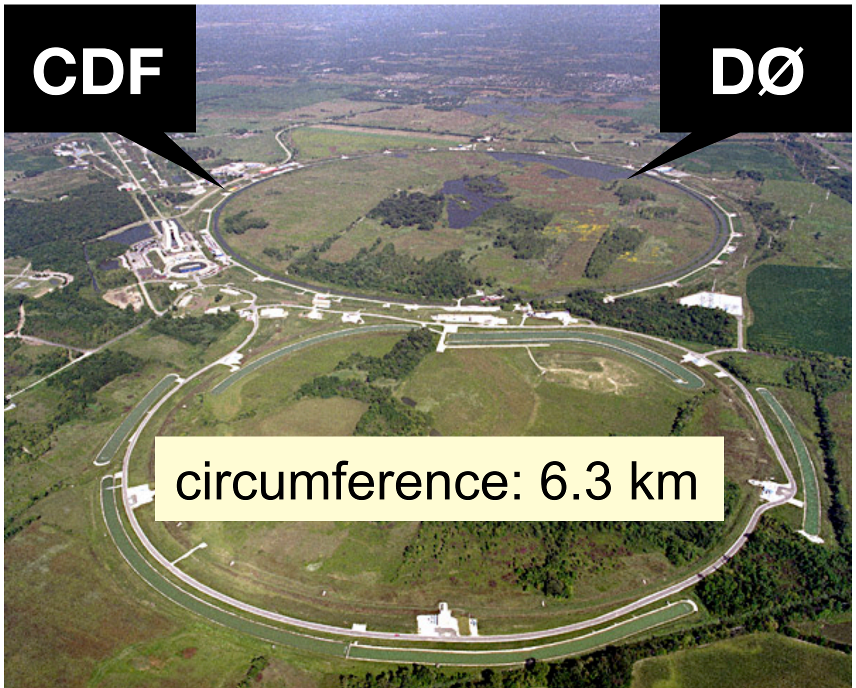
Outline

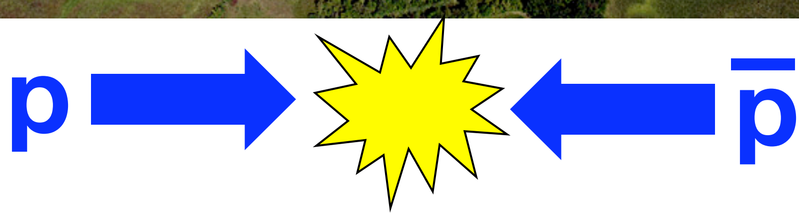
- **The Tools**
  - Tevatron and the CDF experiment
  - LHC and the ATLAS experiment
- **What We Know**
  - The Standard Model
- **What we hope to Discover**
  - Higgs Boson
  - Supersymmetry
- **Conclusions**

The Tools

Current High Energy Colliders

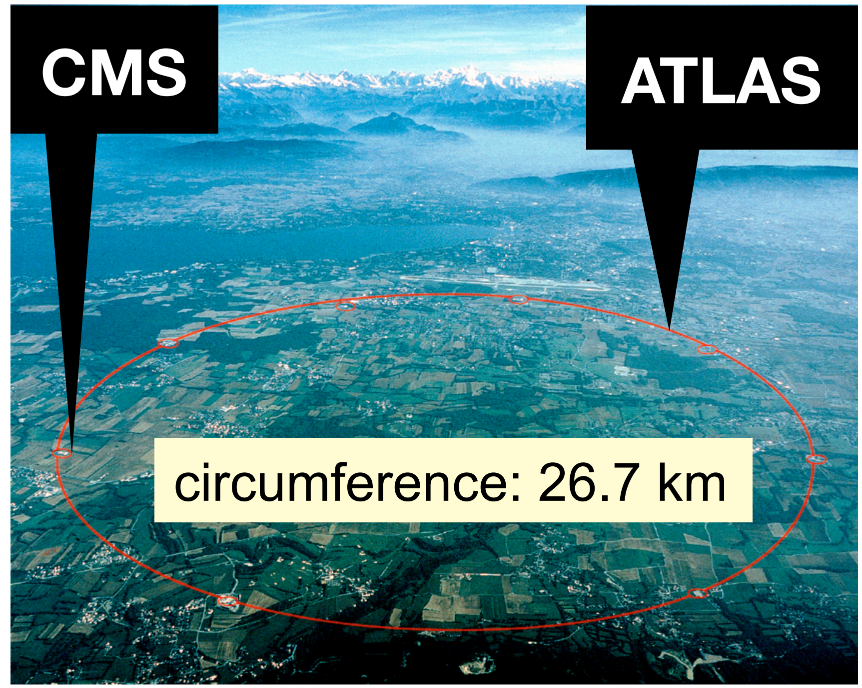
Tevatron

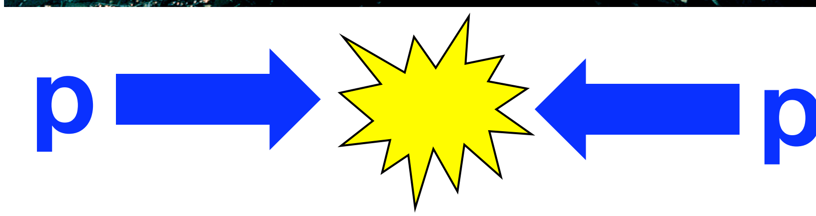




$\sqrt{s}$=1.96 TeV

LHC

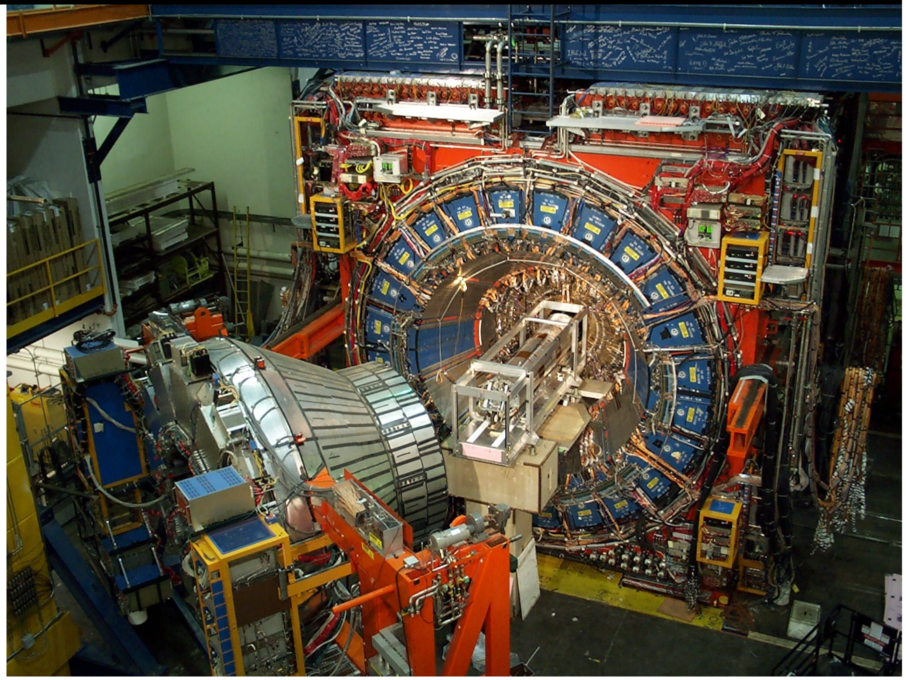


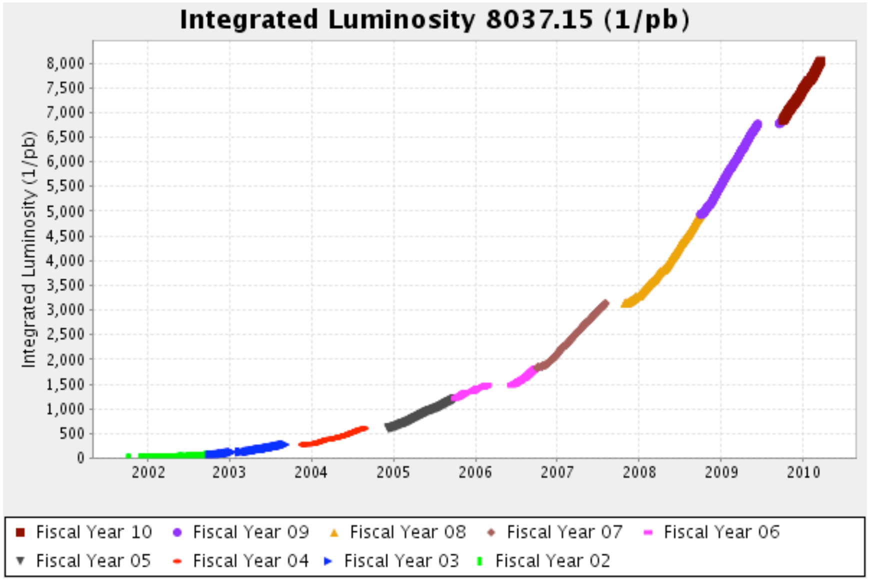


$\sqrt{s} \leq 14$ TeV

CDF at the Tevatron

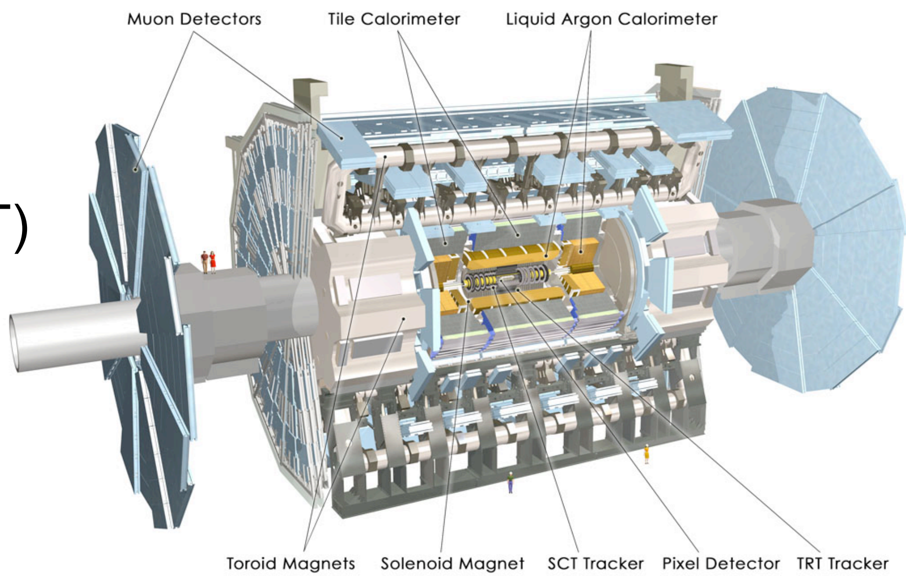
- Multi-purpose detector
  - Tracking
    - Silicon and drift chamber
  - Calorimetry
  - Muon systems
  - Core detector exists since 1985 but many upgrades
    - In particular in ~2000 for "run 2"
- Luminosity:
  - $\int L dt = 8\ fb^{-1}$
  - Recently: ~2 fb^{-1}/yr



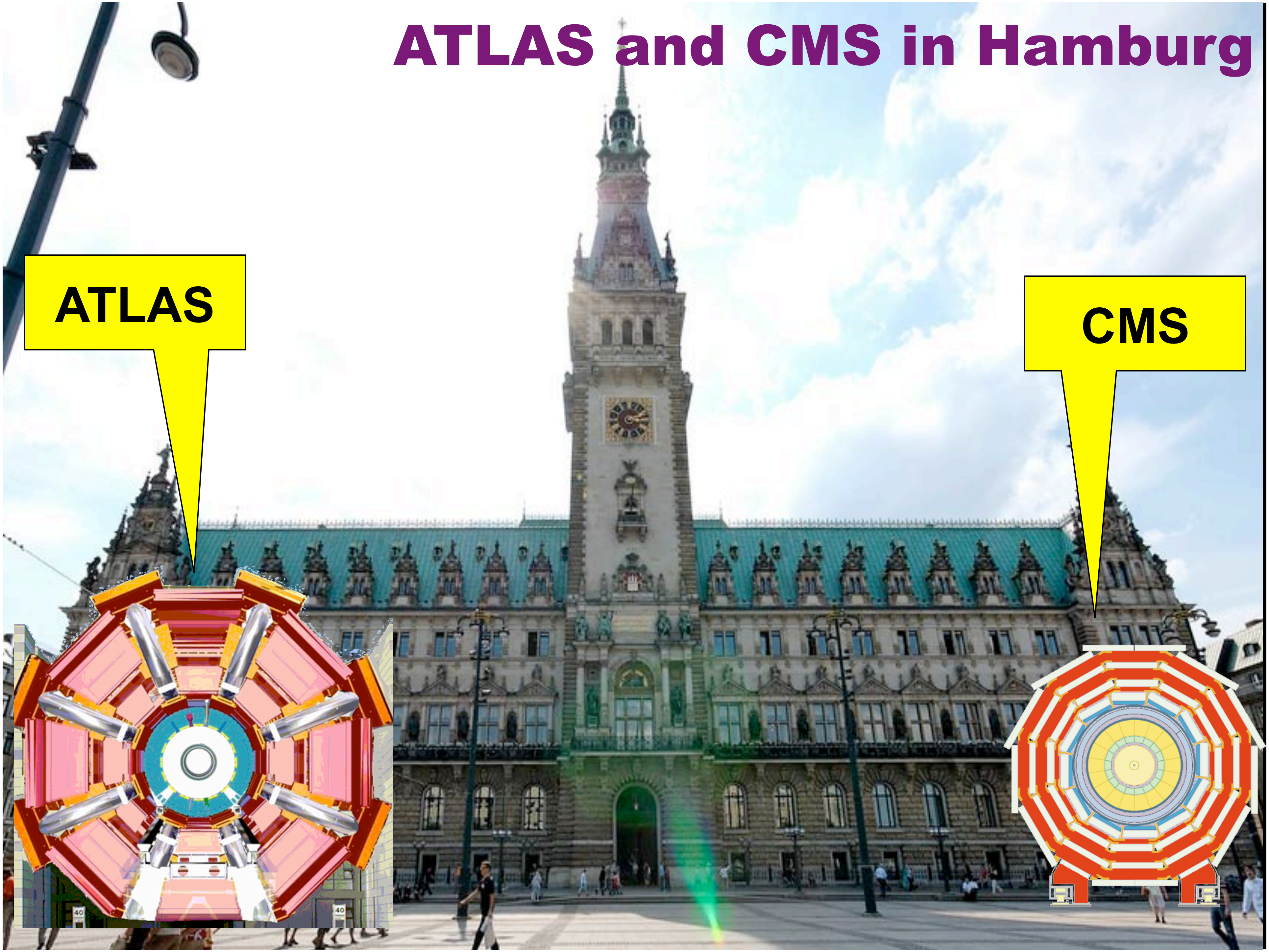


ATLAS at the LHC

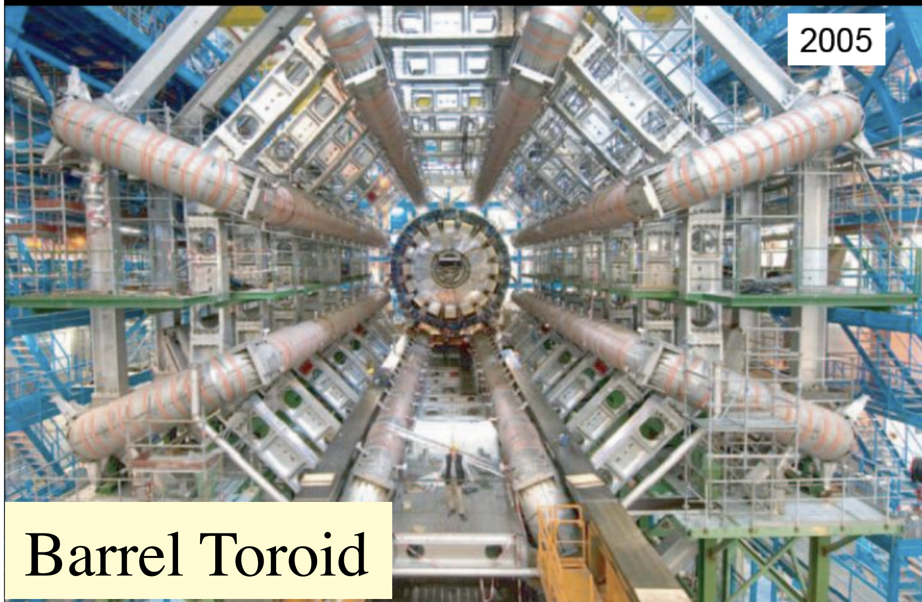
- **Inner Detector: |η|<2.5**
  - Silicon Pixels
  - Silicon Strips (SCT)
  - Transition Radiation Tracker (TRT)
  - Solenoidal magnet (B=2T)
- **Calorimeters: |η|<4.9**
  - EM: Lead/LAr
  - HAD: Steel/scintillator + Cu/LAr
- **Muon System: |η|<2.5**
  - Precision chambers (MDT and CSC)
  - Trigger chambers (RPC and TGC)
  - Air-core toroid magnet (∫BdL=1-7.5 Tm)
- **Several forward detectors**
  - Luminosity measurement

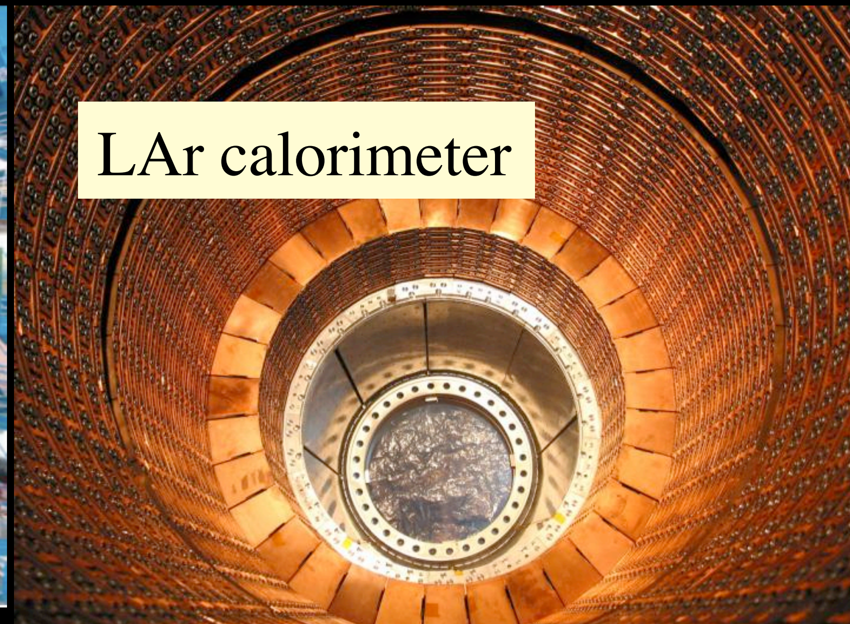


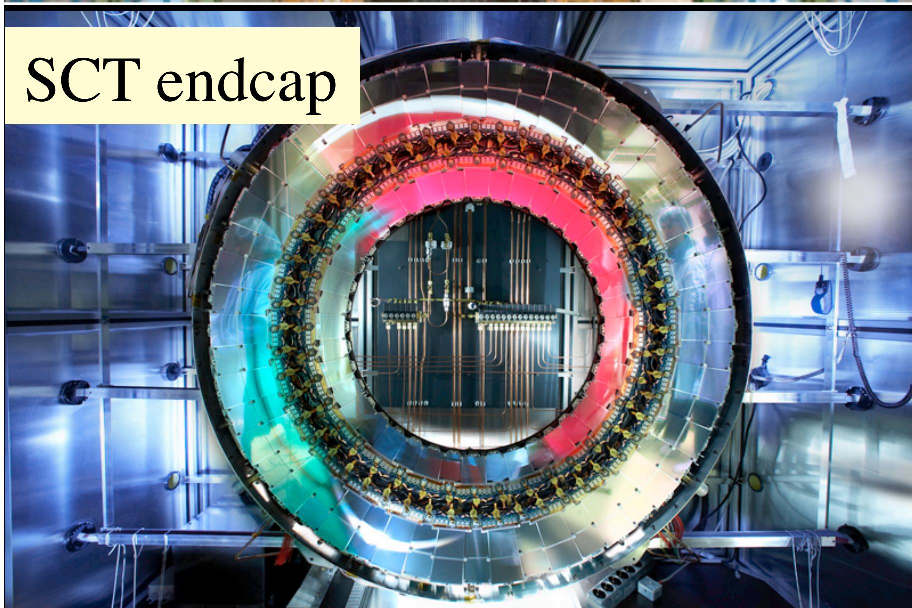
ATLAS and CMS in Hamburg

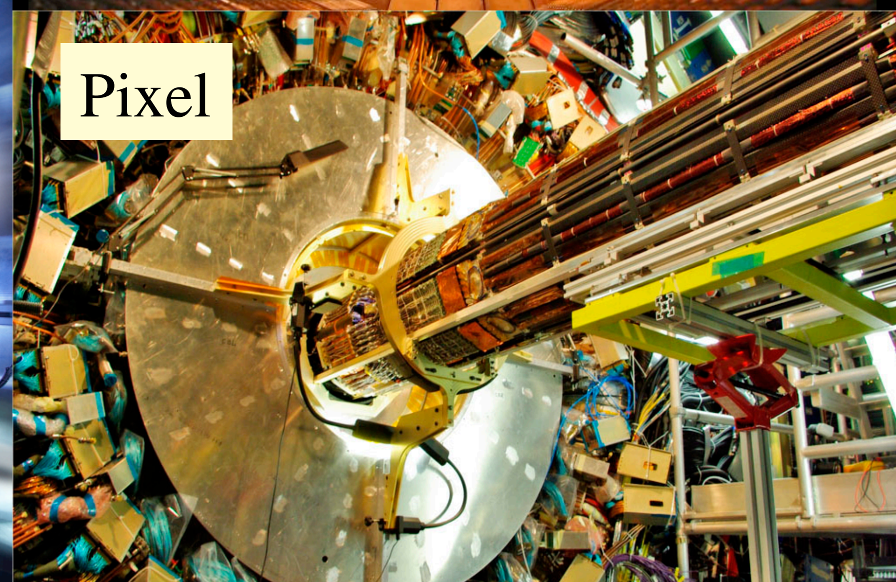


ATLAS Subdetectors

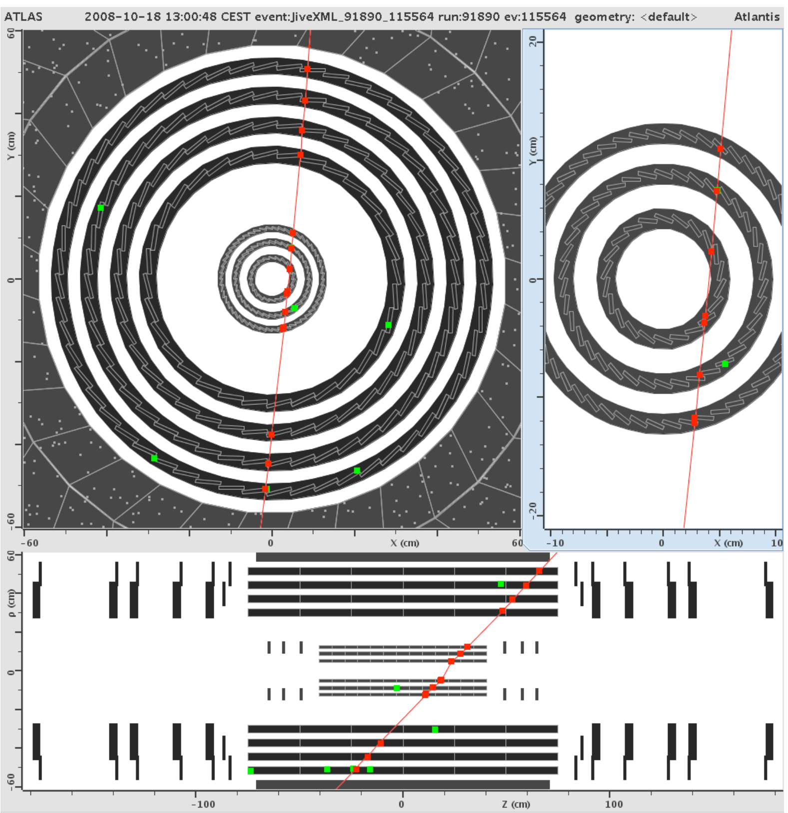




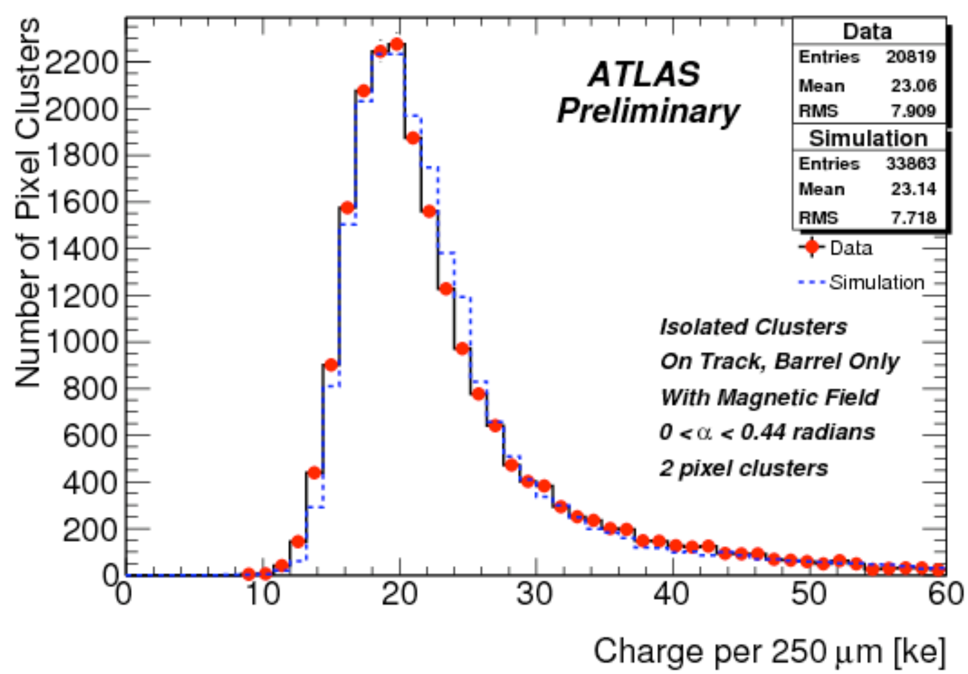




ATLAS Pixel Detector



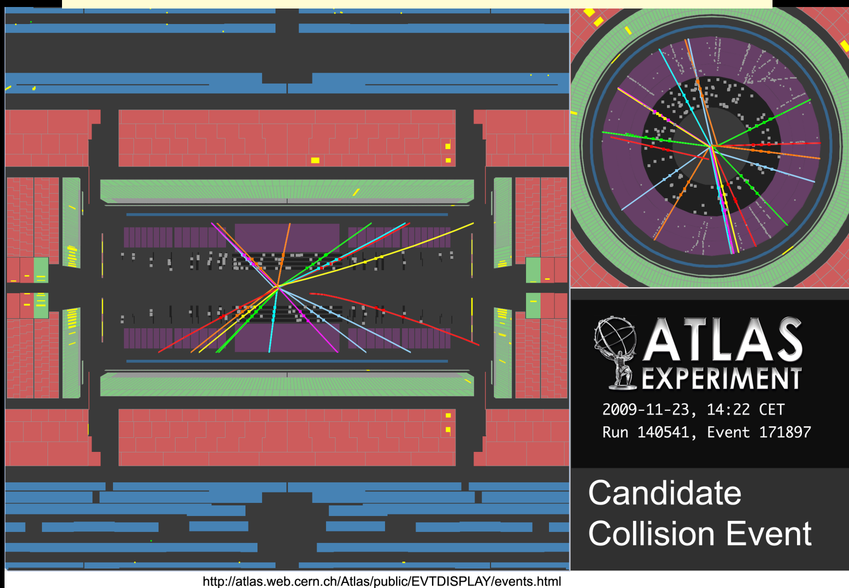
- 80 million pixels in 1744 modules:
  - 3 barrels and 3 disks
  - Pixel size: 50x400 μm
  - Pixel depth: 250μm
  - Noise Occupancy: 10^{-10}
  - Hit efficiency: >99.5%
- Achieved detailed understanding with cosmic ray data (2008/2009)



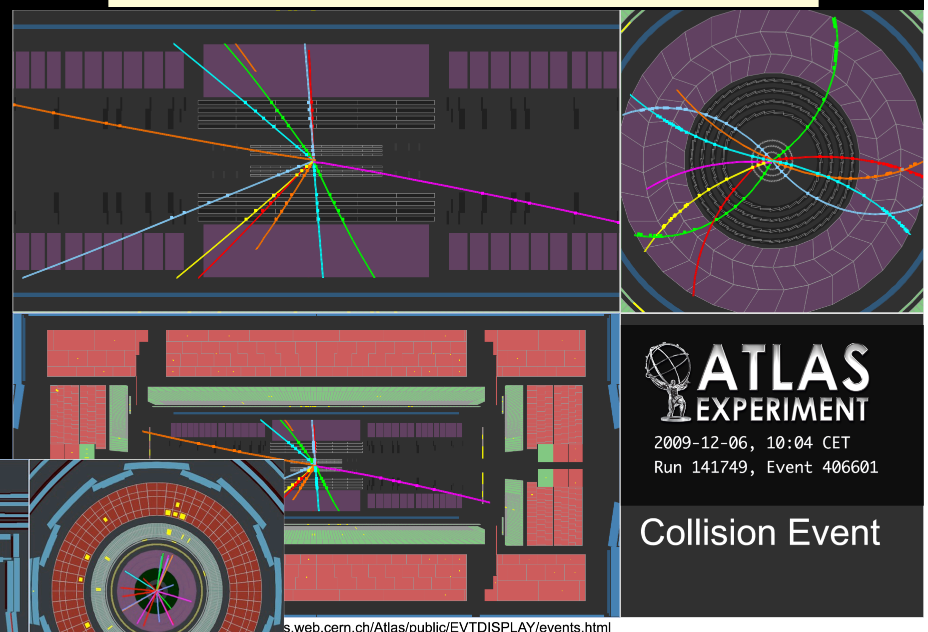

!!! BEAM AT ATLAS !!!
20-11-09 20:47

Collisions in ATLAS!!

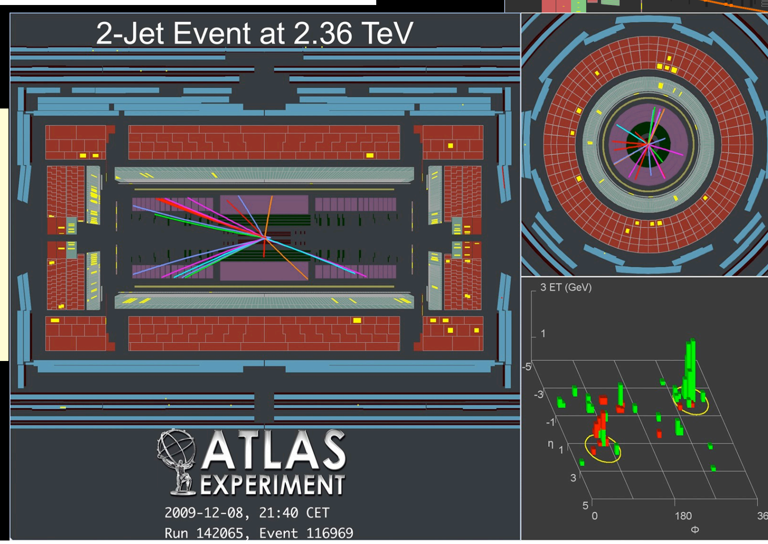
Nov. 23rd: first collisions



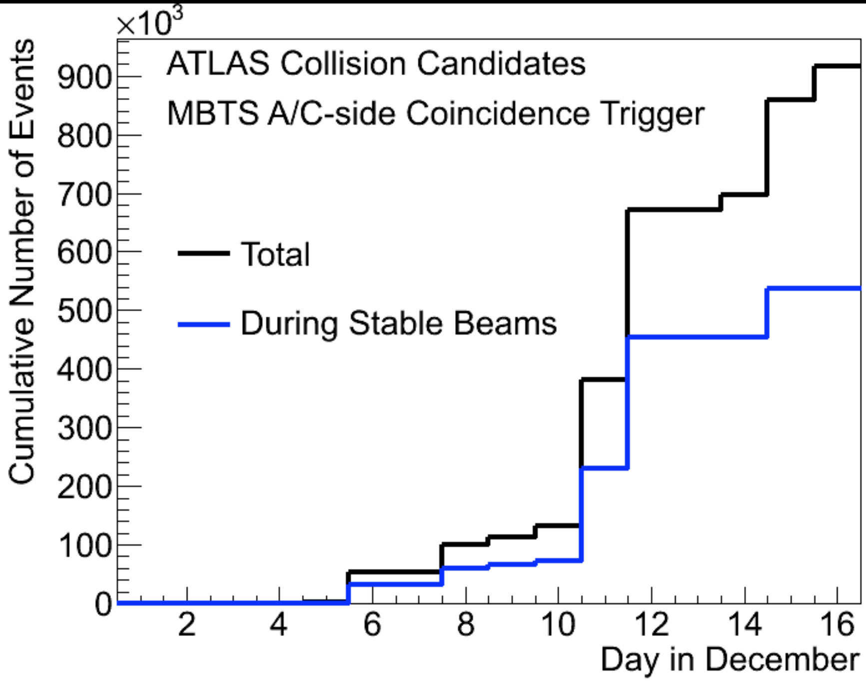
Dec. 6th: first collisions with full detector in nominal conditions

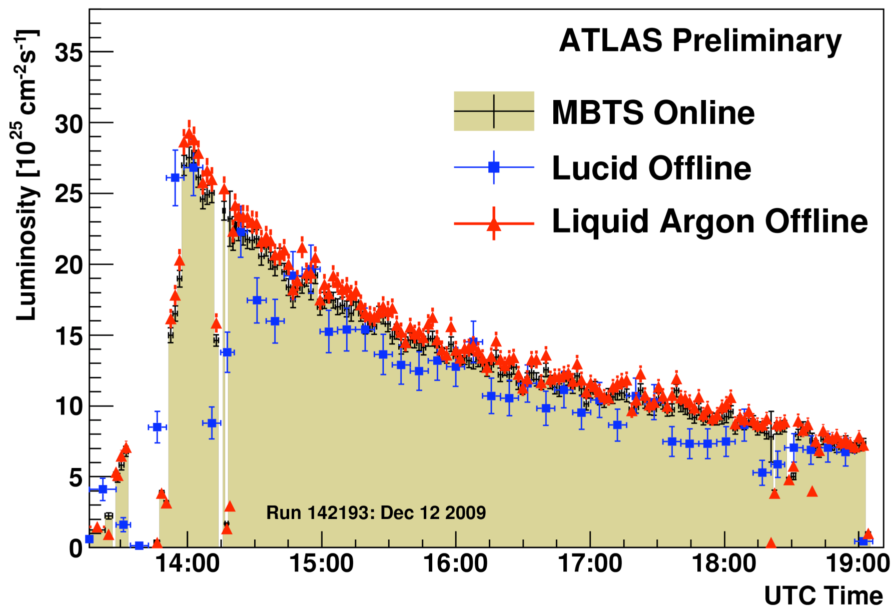


Dec. 8th : first Collisions at $\sqrt{s}$=2.36 TeV



Summary of Data Taking in ATLAS





Recorded data samples	Number of events	Integrated luminosity (< 30% uncertainty)
Total	~ 920k	~ 20 μb^{-1}
With stable beams	~ 540k	~ 12 μb^{-1}
At $\sqrt{s}$=2.36 TeV	~ 34k	≈ 1 μb^{-1}

(First 2010 collisions at $\sqrt{s}$=2.36 TeV taken on March 14th)

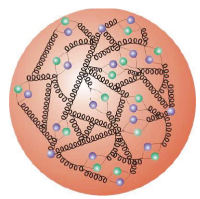
Tevatron vs LHC

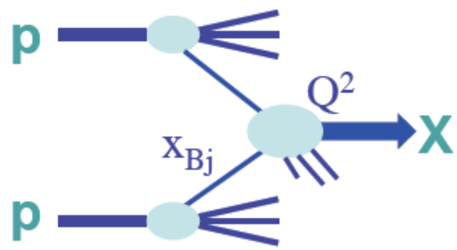
	Tevatron	LHC (2009)	LHC (2010/2011)	LHC (>2012)
$\sqrt{s}$ [TeV]	1.96	0.9-2.36	7	14
# of colliding bunches	36	2-8	≤ 796	2808
Protons/bunch [10^{10}]	9($\bar{p}$)/28(p)	1	7	11.5
Energy stored (MJ)	1	<<1	≤31.2	362
Peak Luminosity [$cm^{-2}s^{-1}$]	3.76×10^{32}	7×10^{26}	$\leq 1.4 \times 10^{32}$	10^{34}
Integrated Luminosity	8 fb^{-1}	20 μb^{-1}	1 fb^{-1}	10-100 fb^{-1} /yr

- Power of 2010/2011 LHC similar to 10 years Tevatron
  - 3.5 times more energy
  - about 10 times less integrated luminosity
  - Design parameters of LHC a lot more powerful

Physics Cross Sections

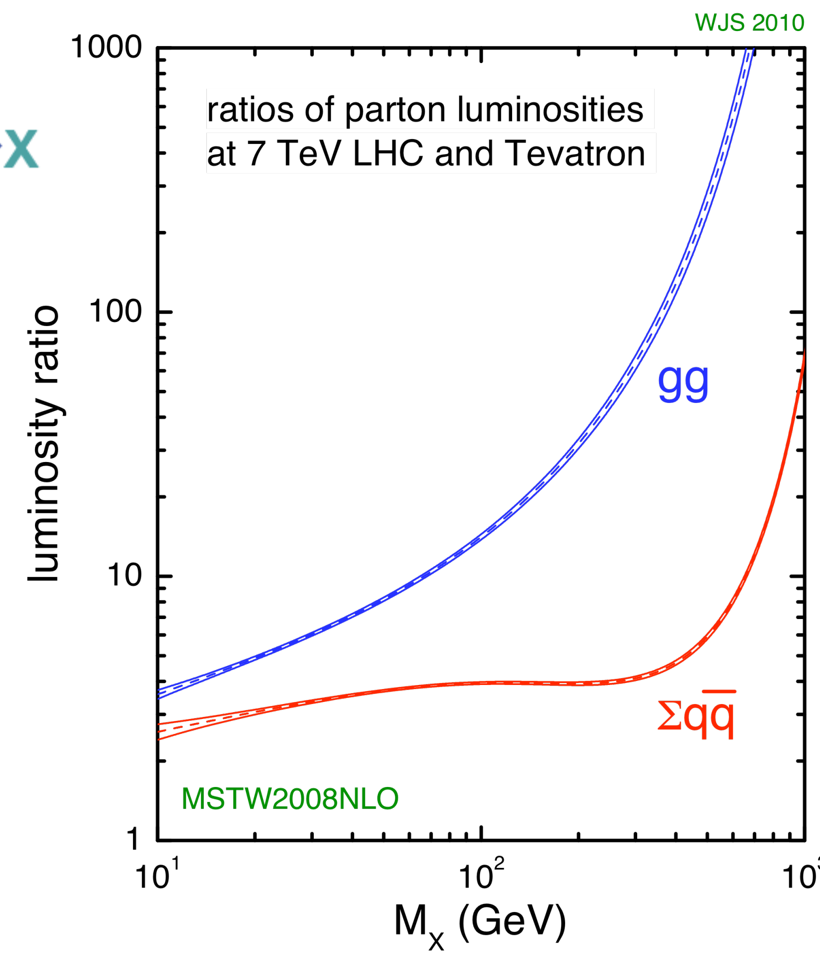
$$M_X = \sqrt{x_1 \cdot x_2 \cdot s}$$





Process	M_X	$\frac{\sigma(\text{LHC @ 7 TeV})}{\sigma(\text{Tevatron})}$
$q\bar{q}\rightarrow W$	80 GeV	3
$q\bar{q}\rightarrow Z'_{SM}$	1 TeV	50
$gg\rightarrow H$	120 GeV	20
$q\bar{q}/gg \rightarrow t\bar{t}$	2x173 GeV	15
$gg \rightarrow \tilde{g}\tilde{g}$	2x400 GeV	1000

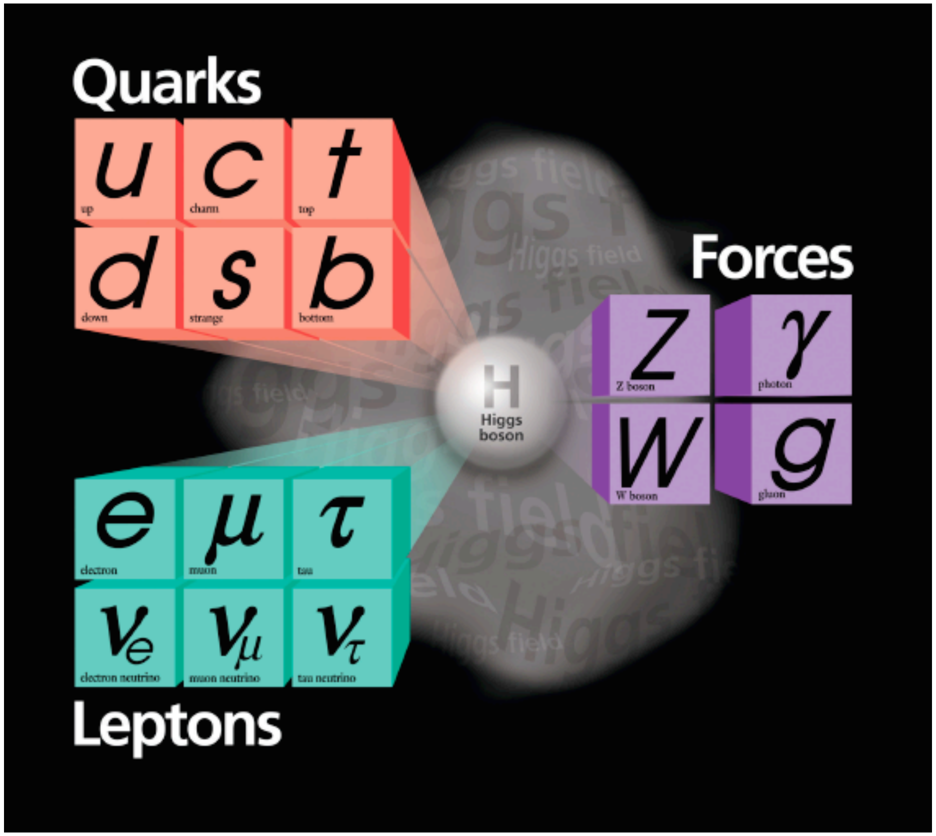
- $\int L dt = 1\ \text{fb}^{-1}$ at LHC already competitive with $10\ \text{fb}^{-1}$ at Tevatron for many physics processes



Precise understanding of Proton composition thanks to HERA

What We Know

Fundamental Particles and Forces

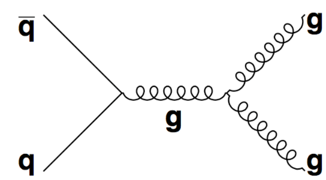


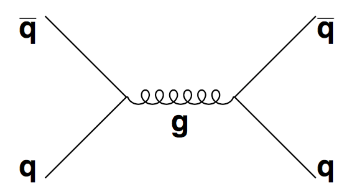
The Standard Model

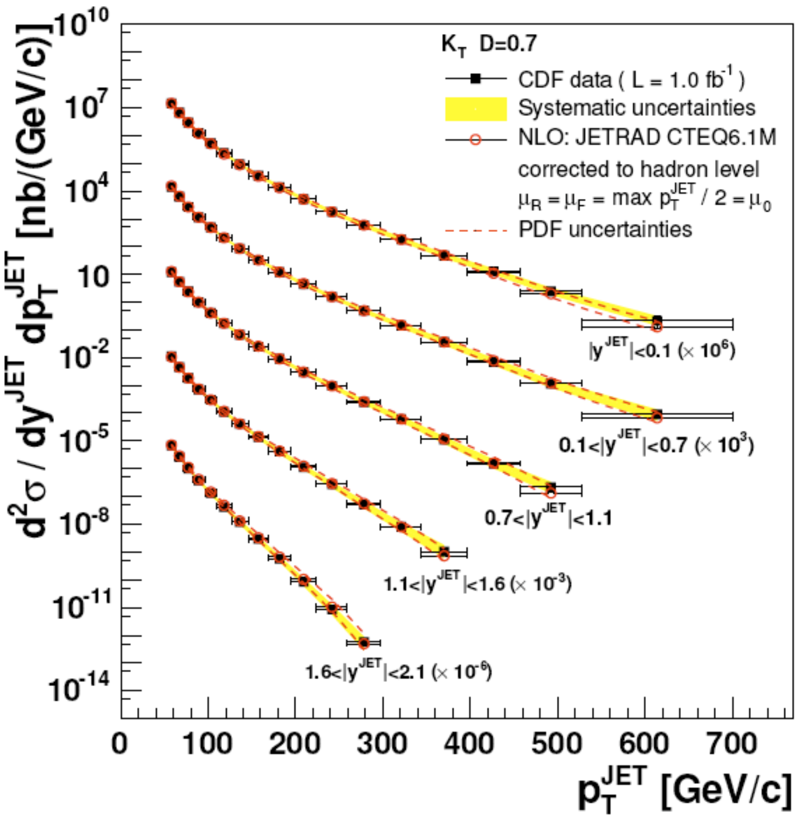
- **Matter**
  - is made out of fermions
- **Forces**
  - are mediated by bosons
- **Higgs boson**
  - Plays critical role
  - Not found yet

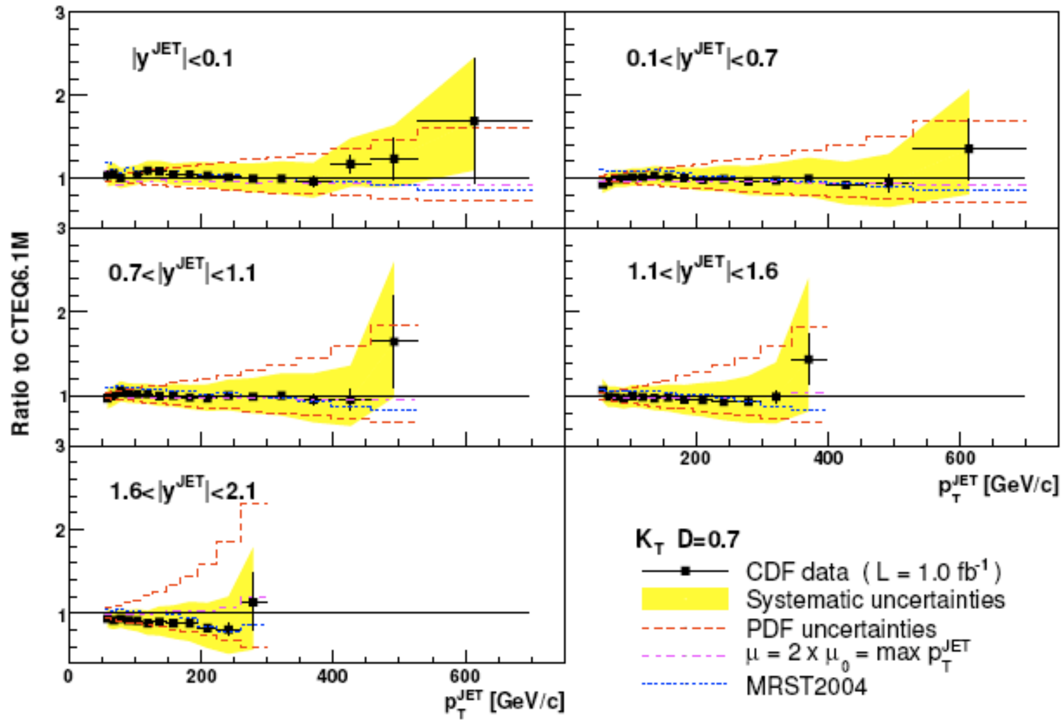
Standard Model very successful in describing all data from collider experiments

Jet Cross Sections



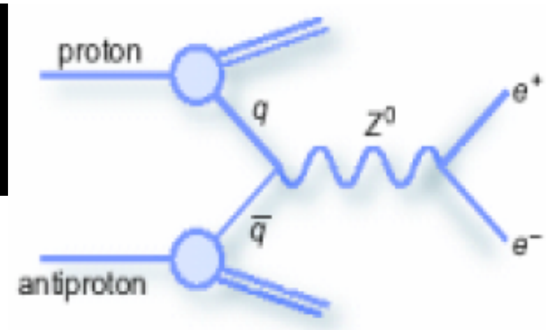


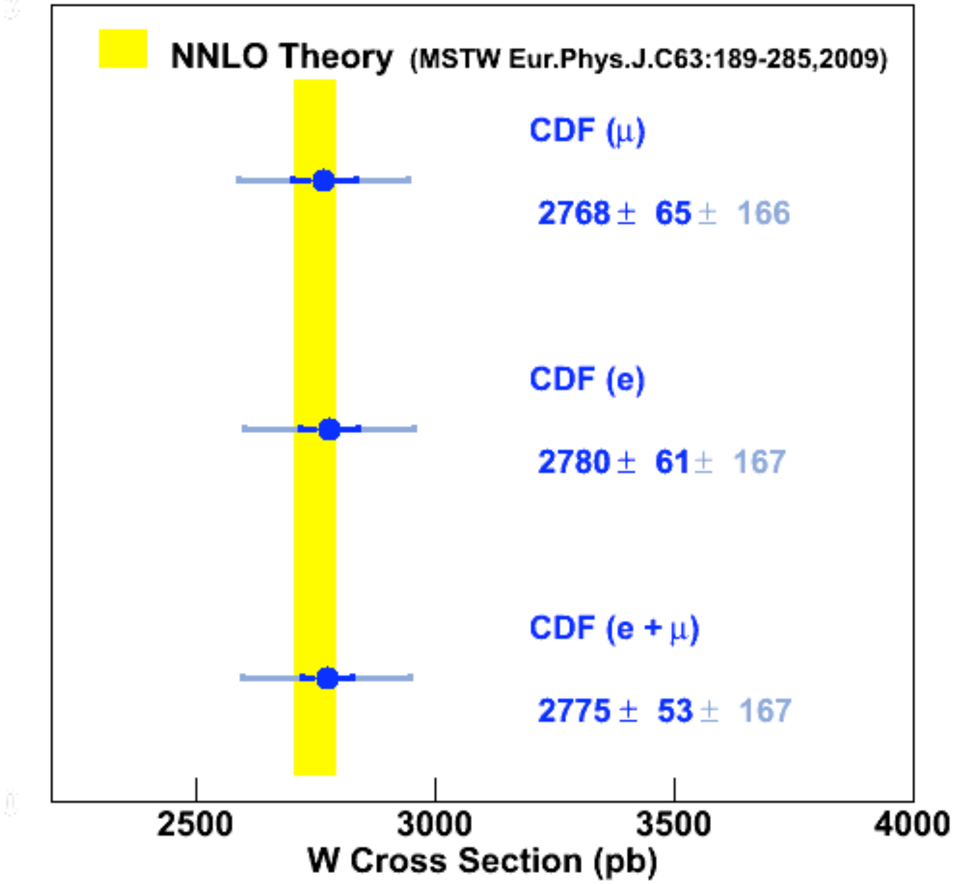


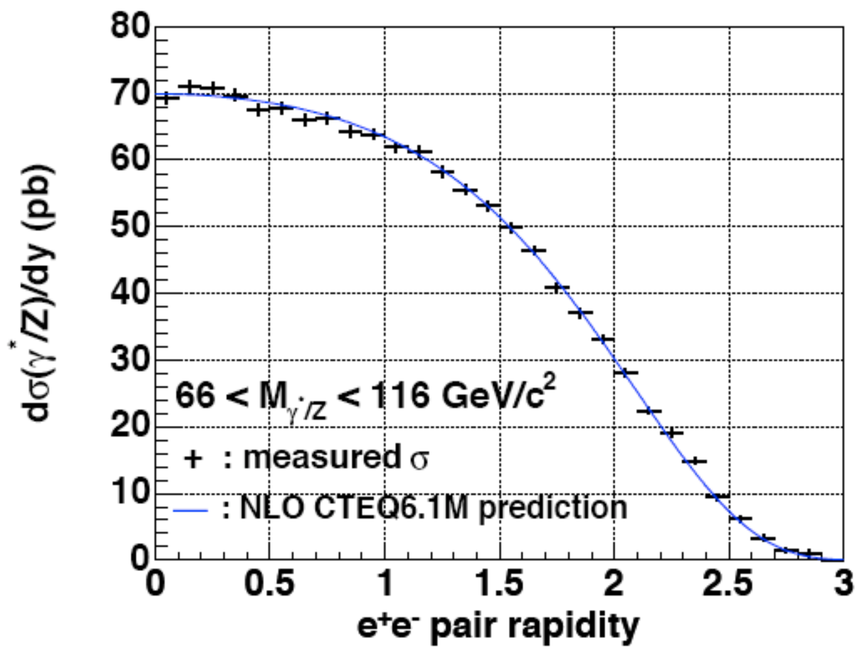


- Measurement agrees well the theoretical prediction
- Largest uncertainties due to parton distribution functions at high x
  - Improves when using these data to constrain high-x gluon

W and Z production

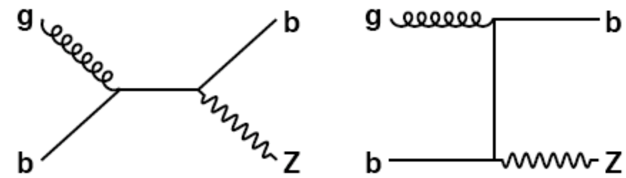






- Experimental precision about 2% (syst.) ⊕ 6% (lumi)
  - test NNLO QCD predictions (precision also ~2%)
  - Could also be used for calculation of luminosity (if theorists agree)

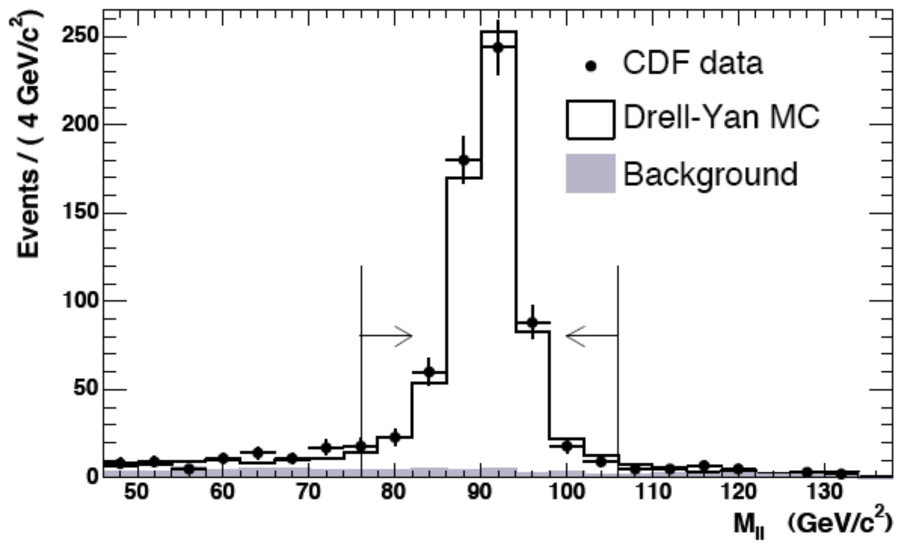
Z+b-jet Cross Section

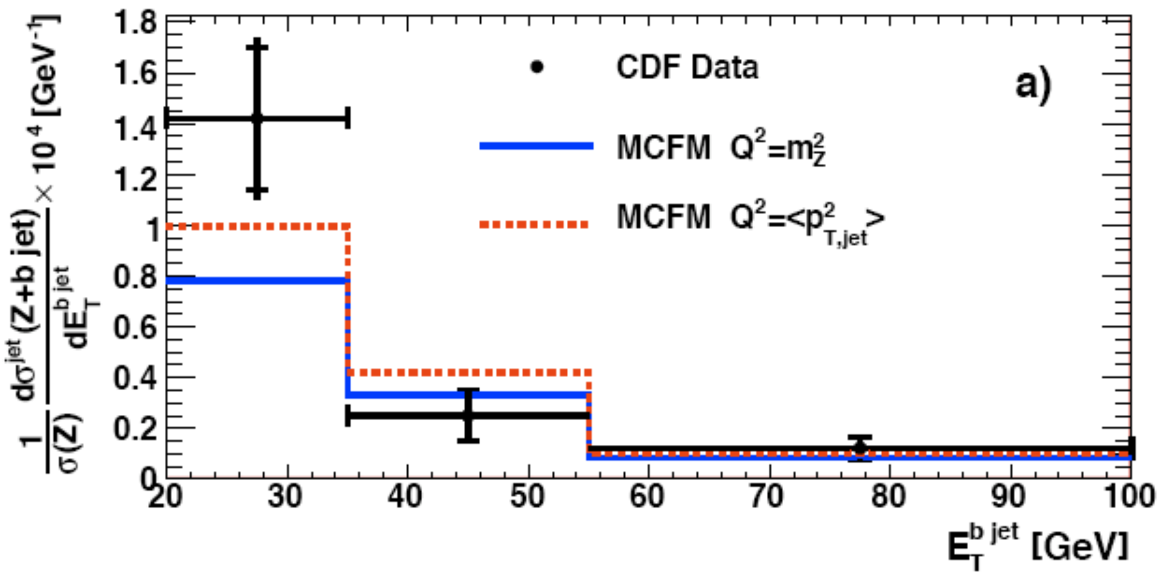


- Z boson and b-jet
  - Related to Higgs Physics
  - Rather rare process in SM

$\sigma(Z\text{+b-jet})/\sigma(Z)=0.332\pm0.068$ %

- Measured cross section versus several kinematic properties
  - Data agree well with theory

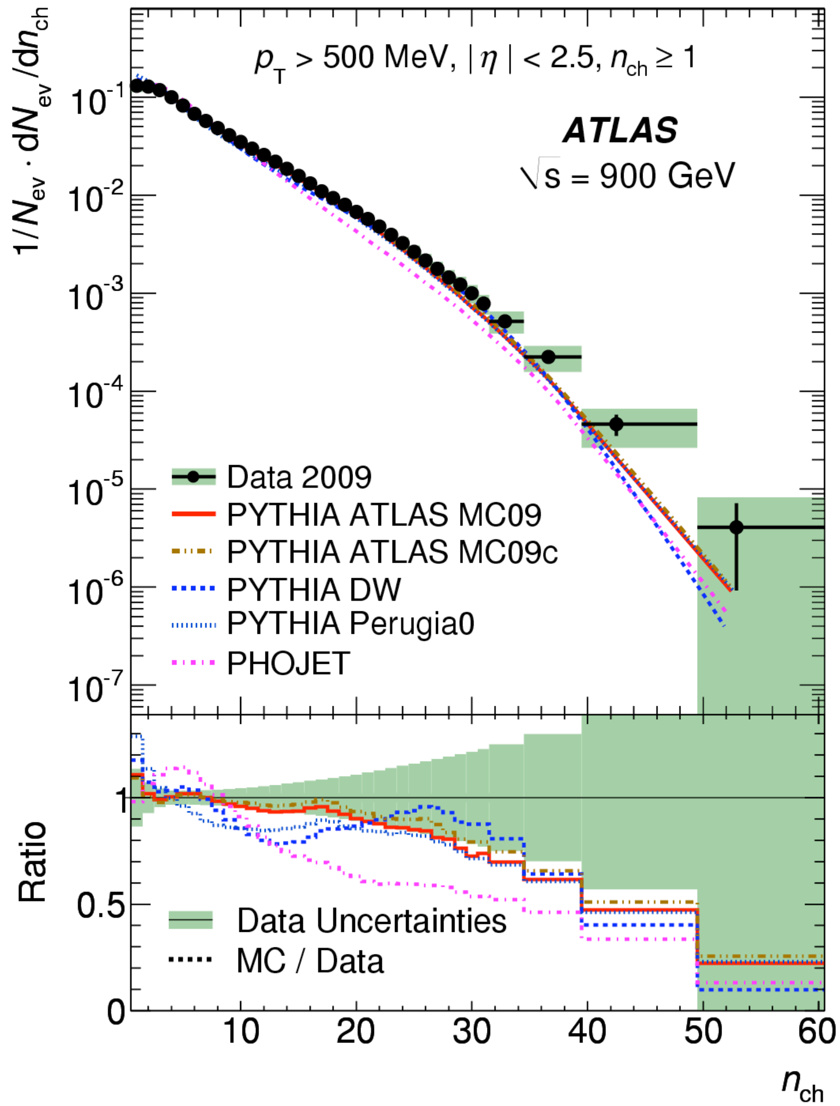




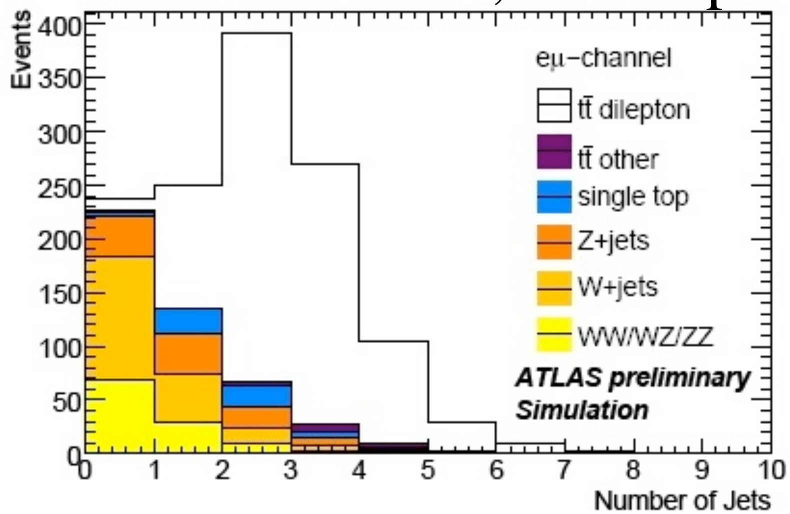
PRD**79**:052008,2009

Testing SM at LHC

arXiv:1003.3124v1



14 TeV, L=200 pb^{-1}



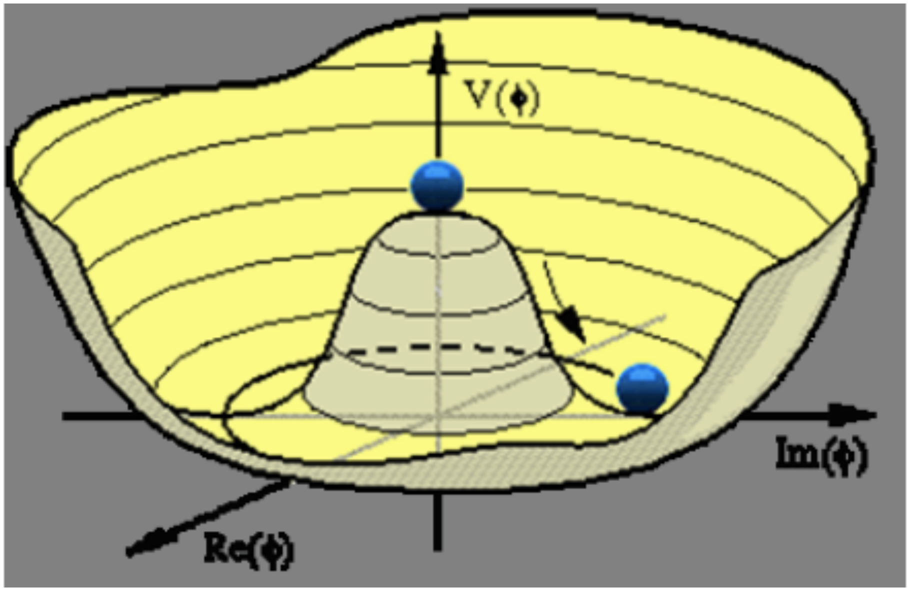
- **Minimum Bias physics**
  - Tune MC models
  - Luminosity measurement
  - High pileup
  - Understand detector
- ….
- **Top physics**
  - Starting with L>10 pb^{-1}

What We Hope to Discover

The Higgs Mechanism

- 1964
  - P. Higgs
  - R. Brout, F. Englert
- New scalar self-interacting field with 4 d.o.f.:

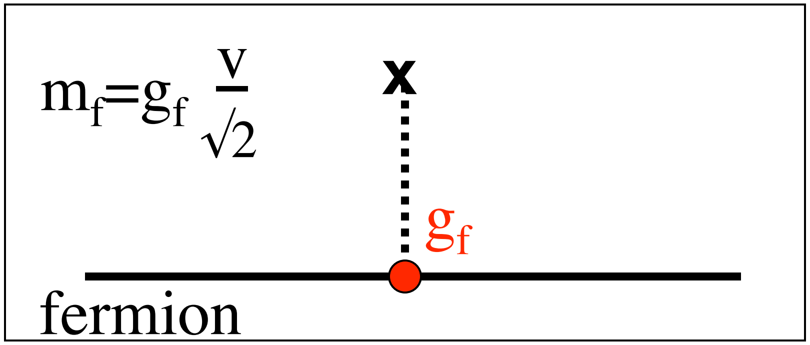
$$V(\Phi) = \frac{\lambda}{4}(\Phi^\dagger\Phi - \tfrac{1}{2}v^2)^2$$



- Ground state: non-zero-value breaks electroweak symmetry generating
  - 3 Goldstone bosons: $W^{\pm}_L, Z_L$
  - 1 neutral Higgs boson

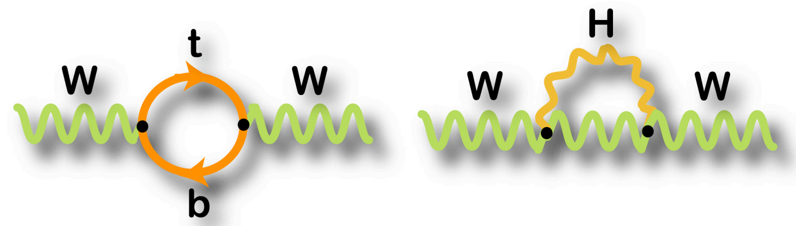
$\langle\Phi^0\rangle = v/\sqrt{2}$, where $v = 246$ GeV.

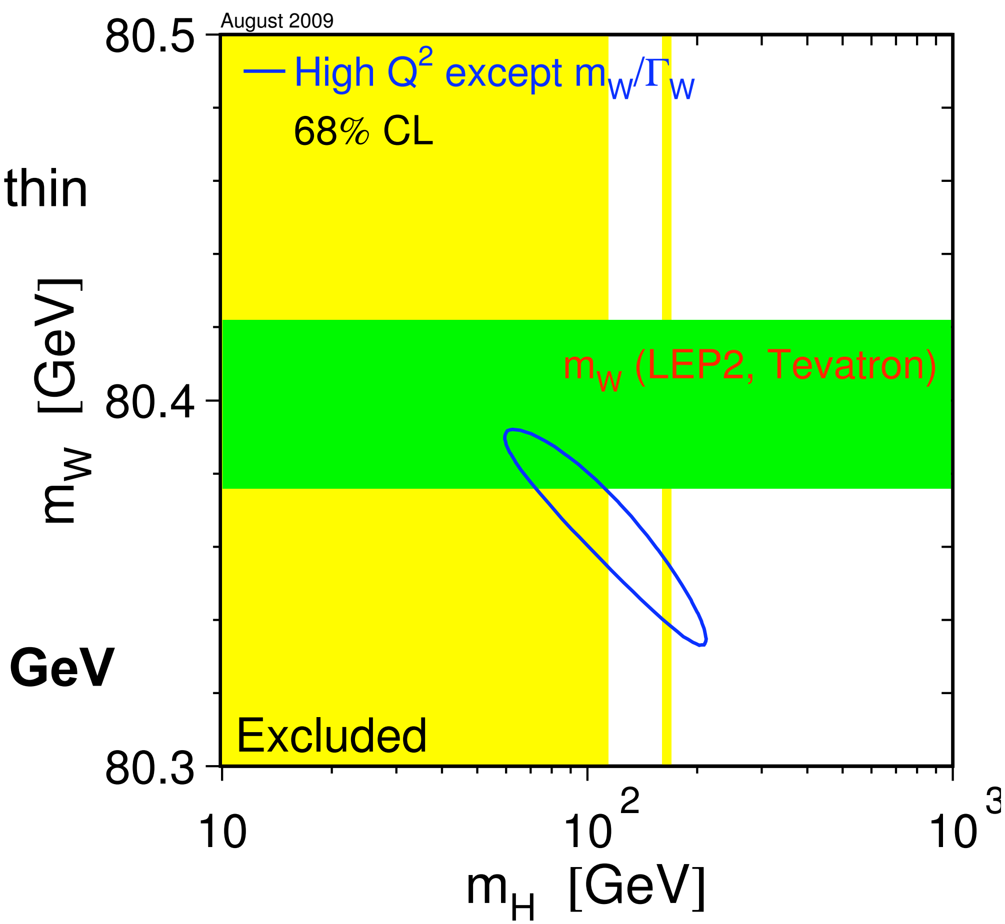
- Masses of fermions m_f proportional to unknown Yukawa couplings g_f



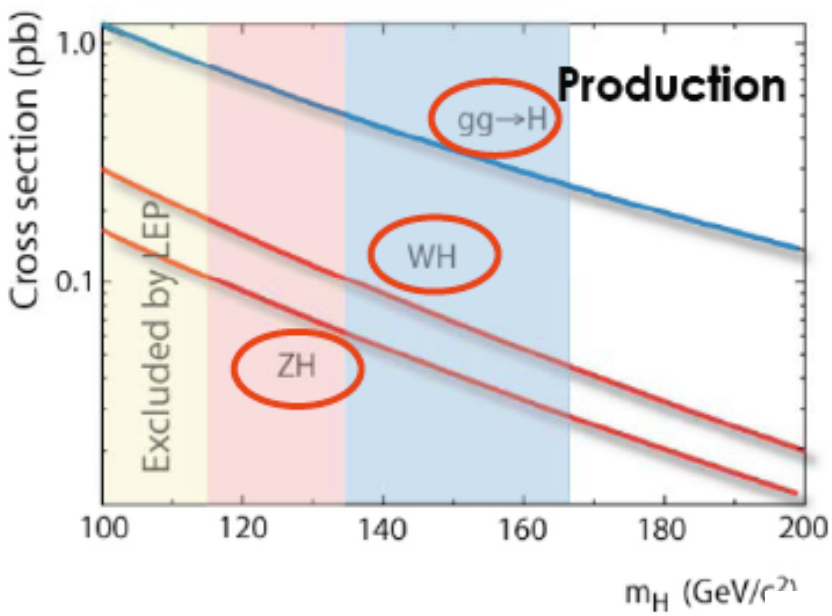
Where is the Higgs boson?

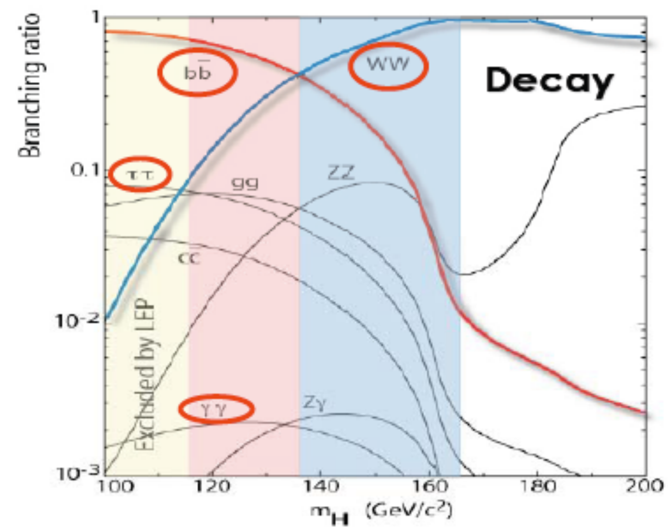
- Precision measurements at Tevatron, LEP and SLC of
  - **M_W =80.399 ± 0.023 GeV/c^2**
  - **m_{top}=173.1 ± 1.2 GeV/c^2**
  - **Z-boson properties**
- Prediction of Higgs boson mass within SM due to loop corrections
  - **$M_H = 87^{+35}_{-26}$ GeV**
  - **M_H<157 GeV at 95% CL**
- Direct limits at 95% CL
  - **LEP: M_H>114.4 GeV**
  - **Tevatron: M_H<163 or M_H>166 GeV**



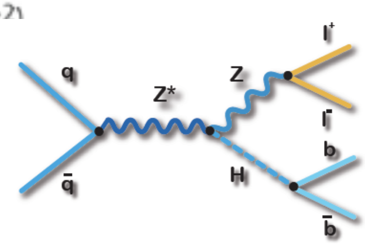


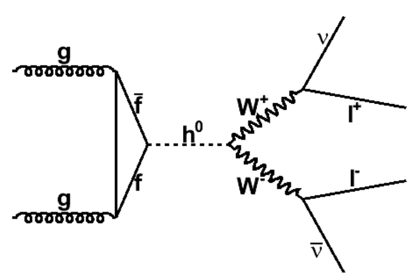
Tevatron Higgs Search

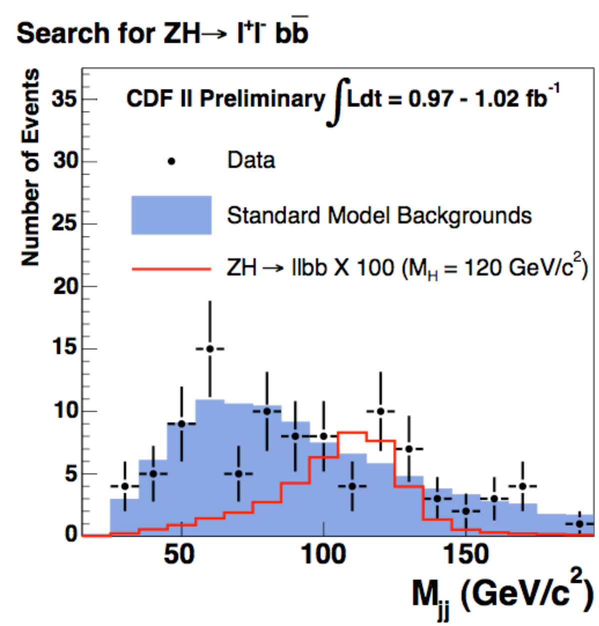




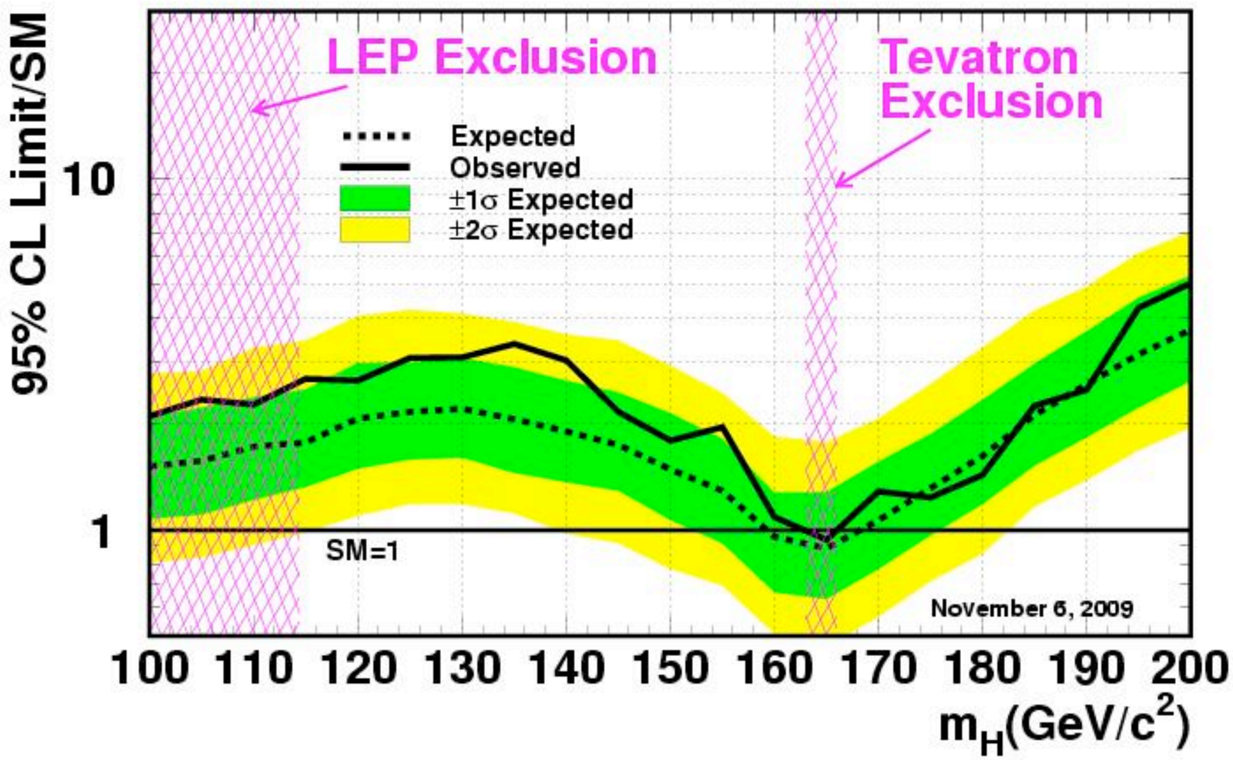
- Low mass:
  - ZH and WH with H→bb
  - Higgs boson expected as peak in bb invariant mass
- High mass:
  - H→WW with W→lν





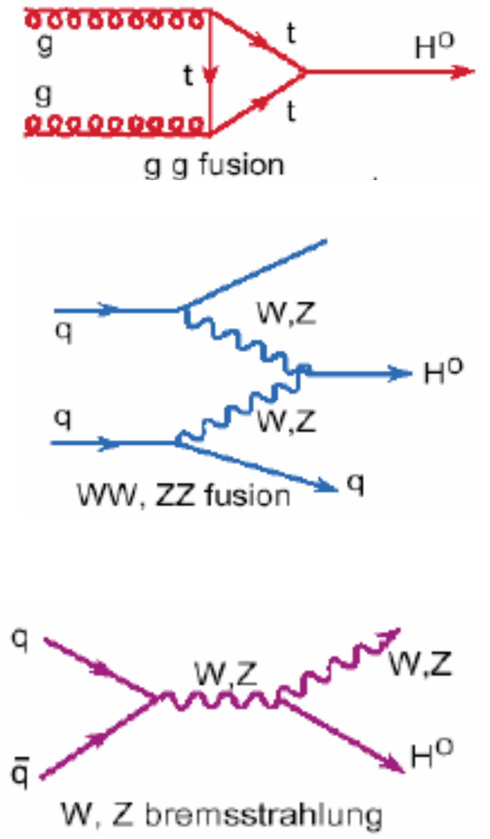


Tevatron Combined Status

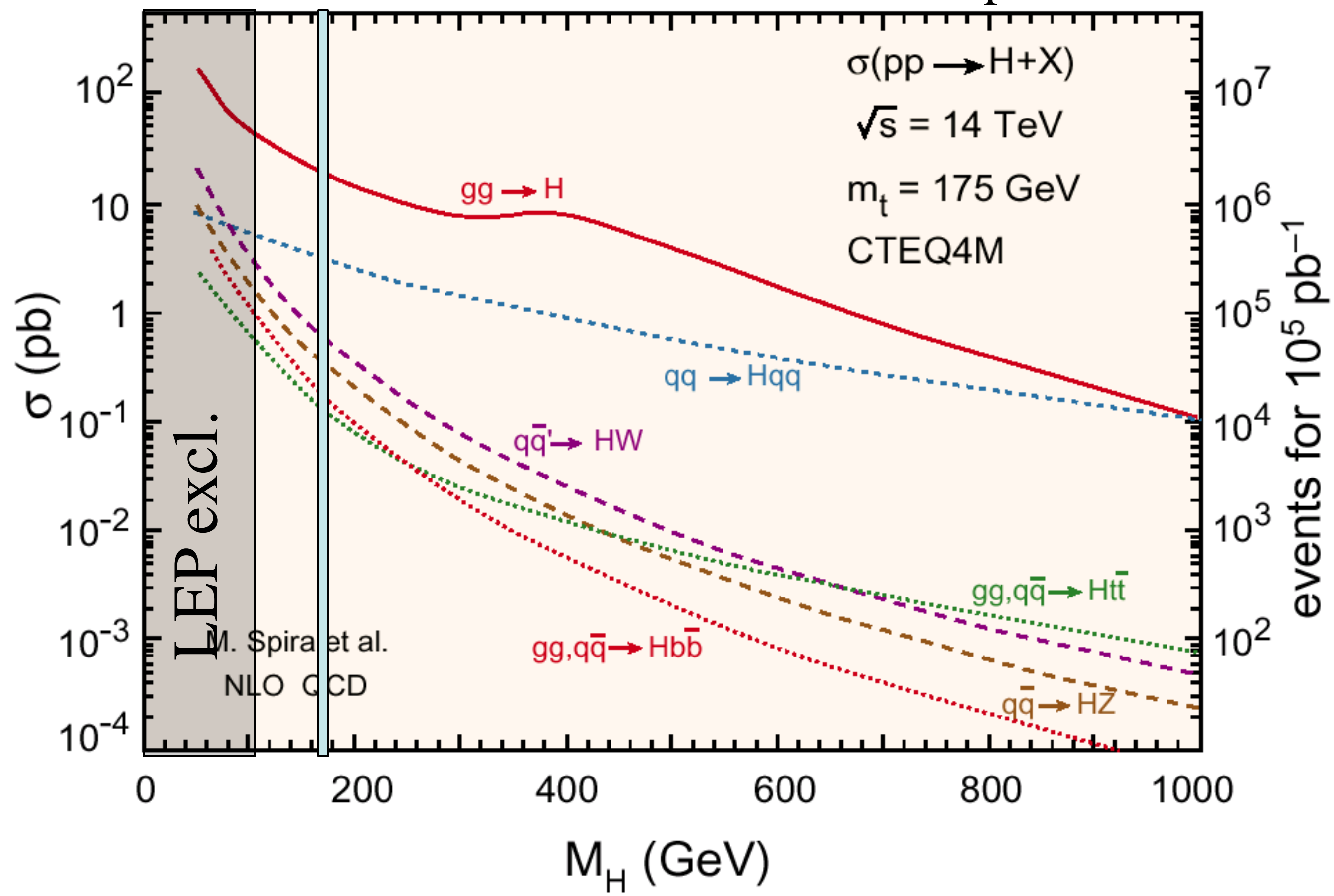


- Combine CDF and DØ analyses from all channels at low and high mass
  - Exclude m_H=163-166 GeV/c^2 at 95% C.L.
  - m_H=120 GeV/c^2: 95% CL limit / SM=2.8

Higgs Production at the LHC

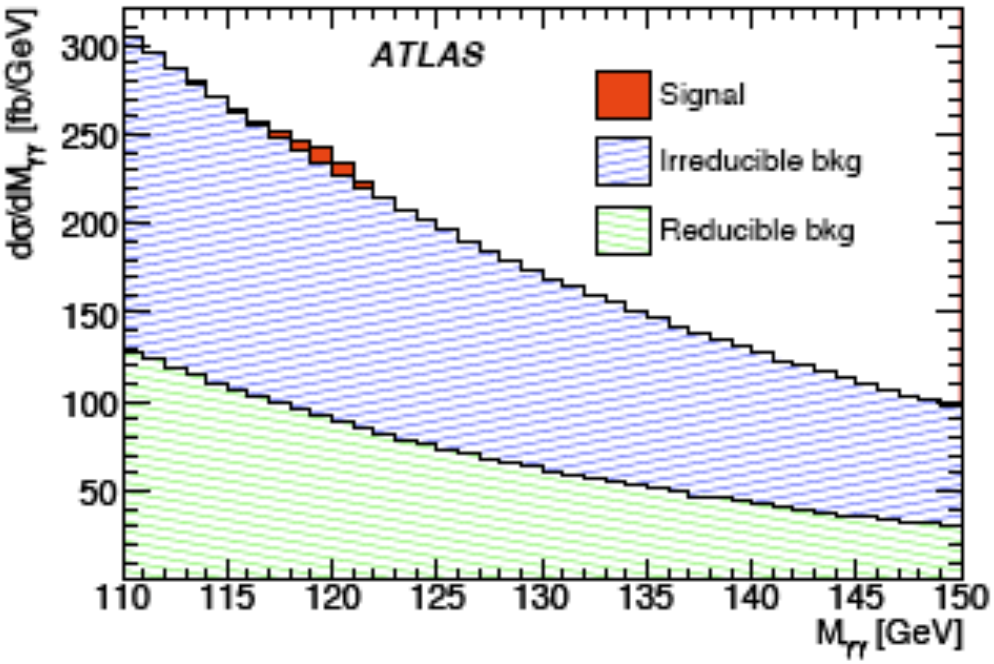


M. Spira *et al.*

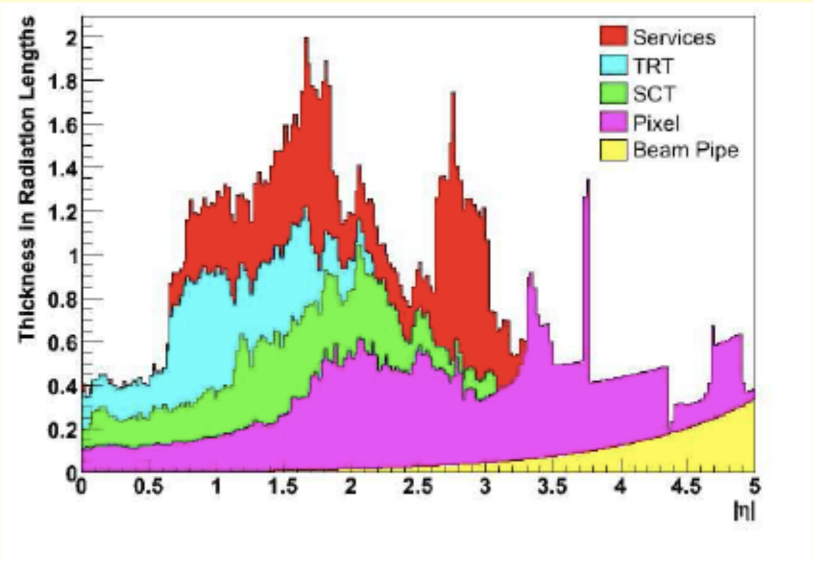


dominant: gg→ H, subdominant: Hqq (VBF)

Low Mass Higgs at LHC

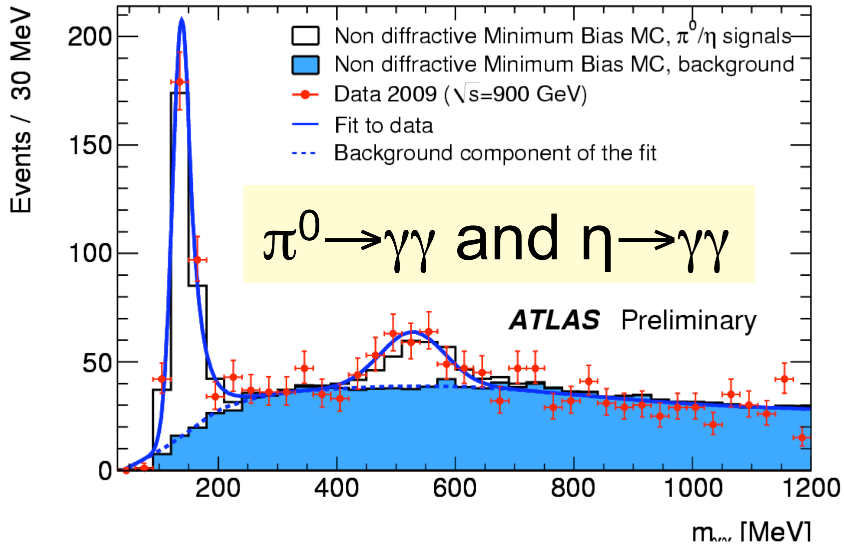


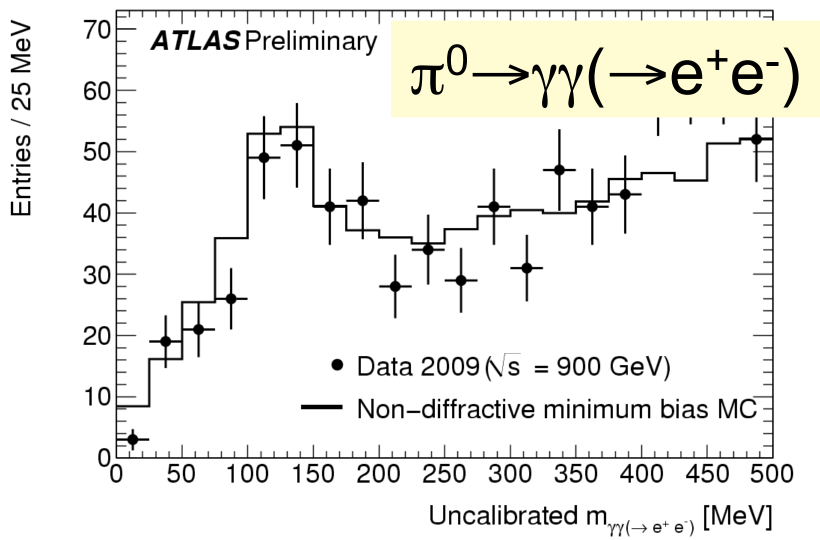
Material (X_0) in front of Calorimeters versus η



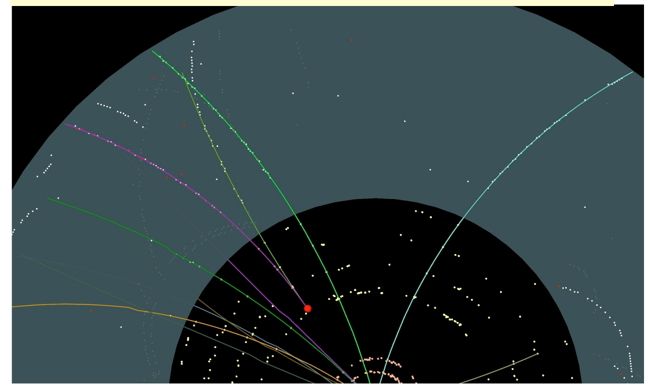
- H→γγ challenges:
  - Large background qq→γγ and from jets (with $\pi^0 \rightarrow \gamma\gamma$)
  - Mass resolution is key: requires brilliant calibration
  - At least 1 photon converts in 50% of events
    - Important to understand detector material
- VBF: Hqq→ττqq also very promising and important channel

Photons and Conversions in 2009

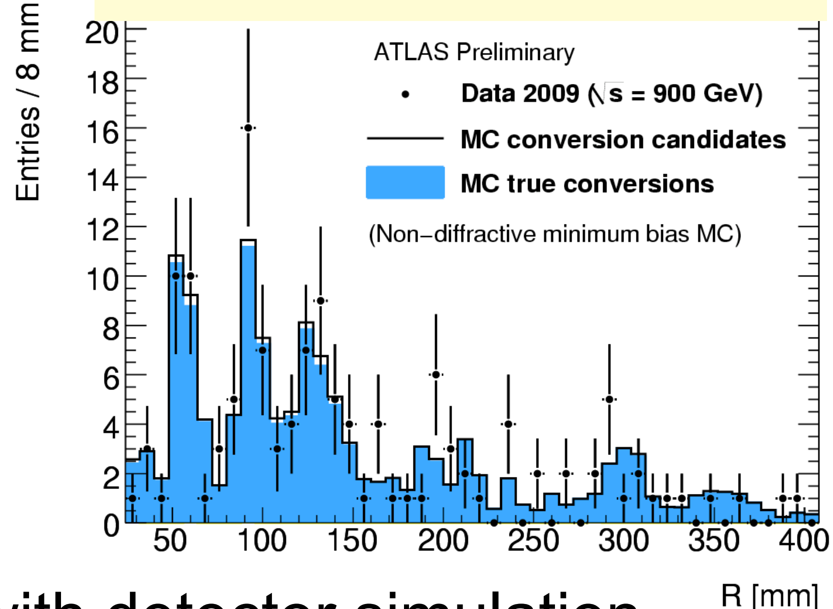




Conversion: $\gamma \to e^+e^-$



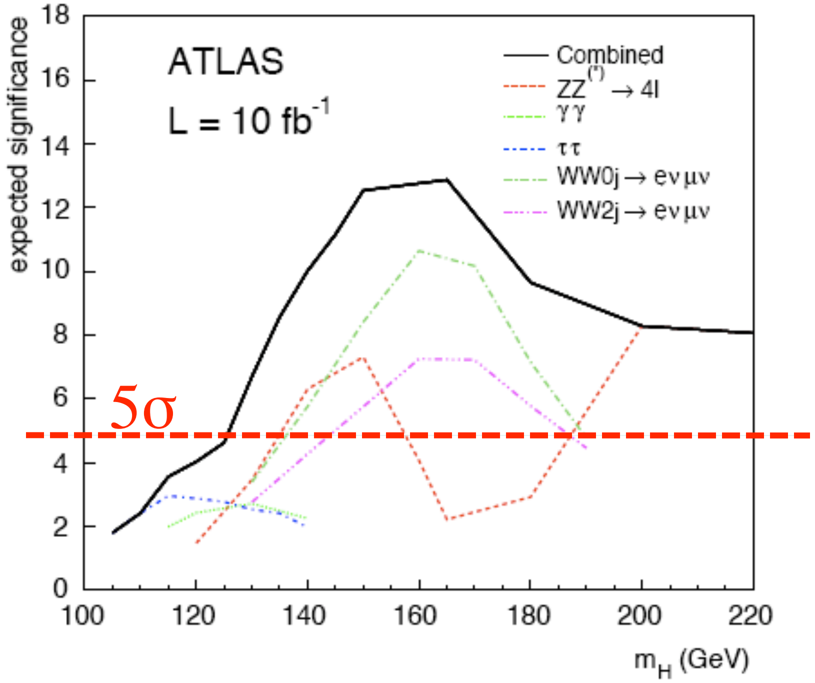
Location of Conversions

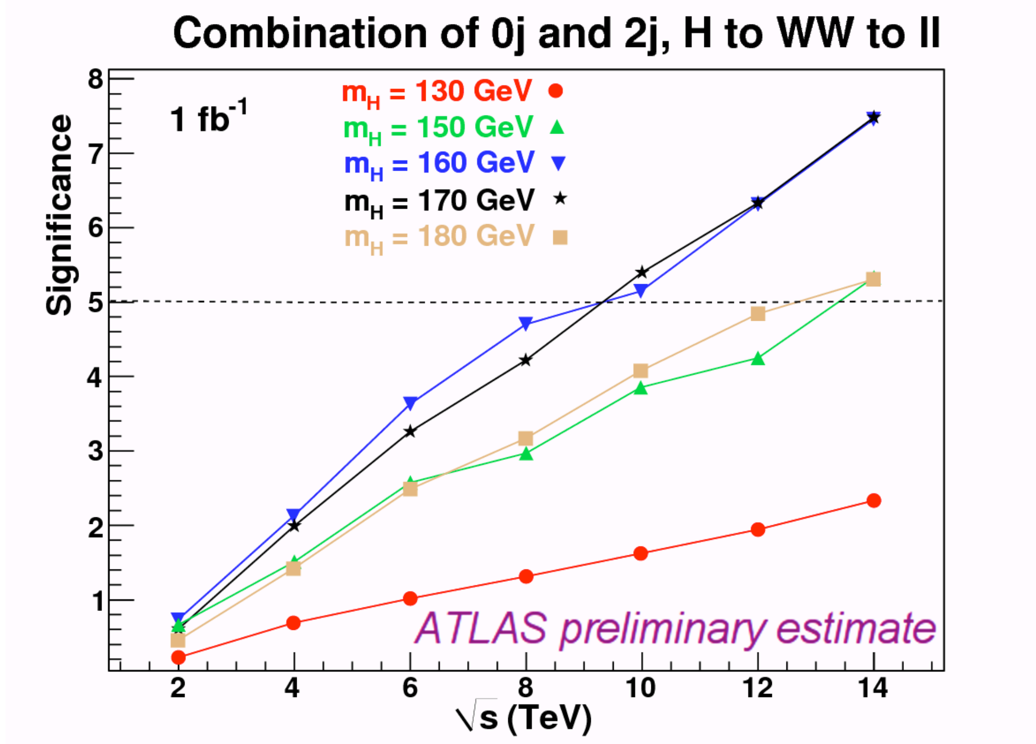


- Very good agreement of data with detector simulation

Higgs Discovery Prospects

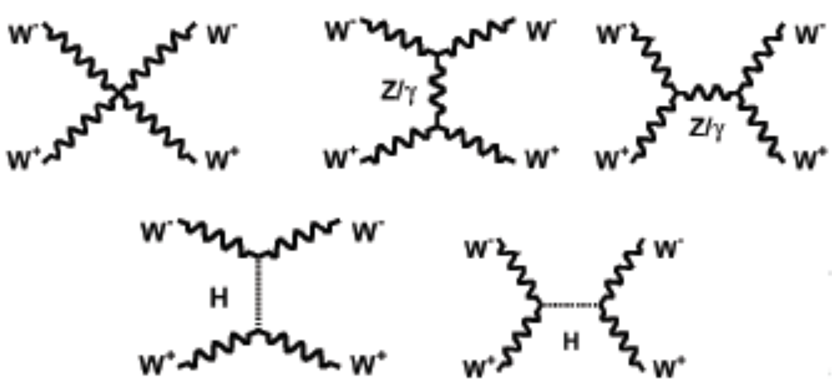
$\sqrt{s}$=14 TeV





- Sensitivity best for M_H=150-180 GeV/c^2
  - Mostly provided by WW decay channel
  - Improve upon current Tevatron sensitivity with L=1 fb^{-1}
- At low mass require more than 10 fb^{-1}
  - Cannot be addressed with the 2010/2011 LHC run

What if there is no Higgs Boson?



$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

Cancellation of terms if Higgs boson exists with M_H<800 GeV/c^2

- **$W_L W_L$ cross section increases with energy**
  - Violates unitarity at $\sqrt{s}$~1.4 TeV!
- **Thus some new physics must be there**
  - E.g. W bosons are composite
    - similar to pion-pion scattering in 1960's

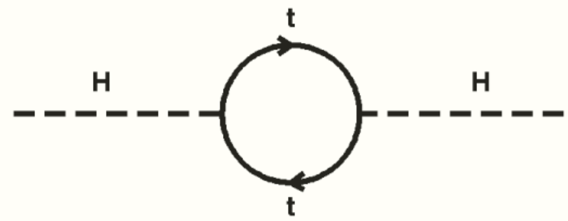
Something New Has to be Found at LHC

Supersymmetry

The Hierarchy Problem

$$m_{H,obs}^2 = m_{H,bare}^2 + \Delta m_{top}^2 + \ldots$$

and $$\Delta m_{top}^2 = -6 \frac{h_t^2}{4\pi^2} \frac{1}{r_H^2} \approx -M_{NP}^2$$



- **Unnatural fine-tuning**
  - If no New Physics (NP) up to M_{Pl}:
    - $r_H \approx 1/M_{Pl}$

$$\boxed{\frac{\Delta m_{top}}{m_{H,obs}} \approx \frac{M_{Pl}}{M_W} \approx 10^{17}}$$

  - Free parameter $m_{H,bare}$ needs to be "fine-tuned" by 10^{17} to cancel huge correction of top loop
- **Can be solved by new particles with $M_{NP} \approx 1$ TeV**
  - Already quite bad for $M_{NP} = 10\ TeV$

$$\boxed{\frac{\Delta m_{top}}{m_{H,obs}} \approx \frac{M_{NP}}{M_W} \approx 10^2}$$

Analogy in Electromagnetism

- Electron mass problem: *[H. Murayama]*
  - Free electron has Coulomb field: $\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}.$
  - Mass receives corrections due to Coulomb field:
    - $(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_{\text{Coulomb}}.$
    - With $r_e < 10^{-17}$ cm: $\frac{\Delta E_{\text{Coulomb}}}{m_e c^2} \approx 6 \cdot 10^3$

- Solution: the positron (pair production) *[Dirac, Weyl]*

$$\Delta E = \Delta E_{\text{Coulomb}} + \Delta E_{\text{pair}} = \frac{3\alpha}{4\pi} m_e c^2 \log\frac{\hbar}{m_e c r_e} \approx 9\% m_e c^2 \text{ for } r_e = \ell_{Planck}$$

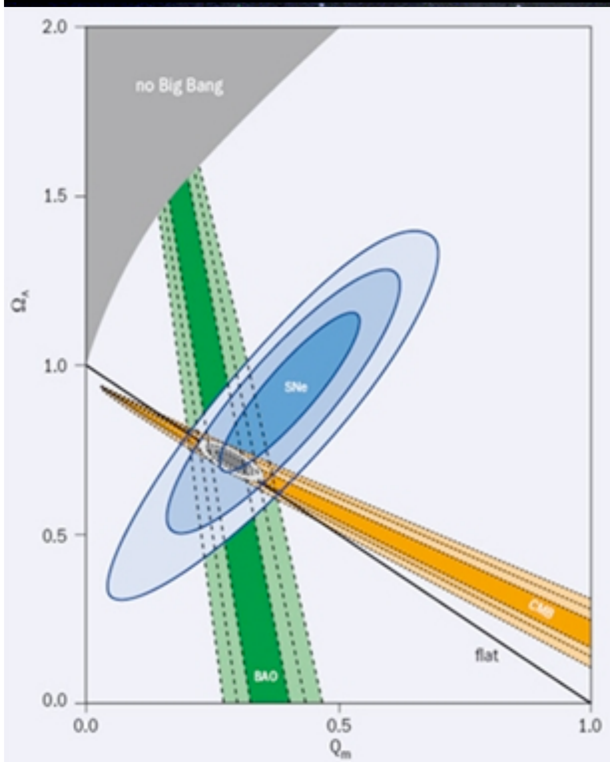
Problem was solved by new particles:
anti-matter

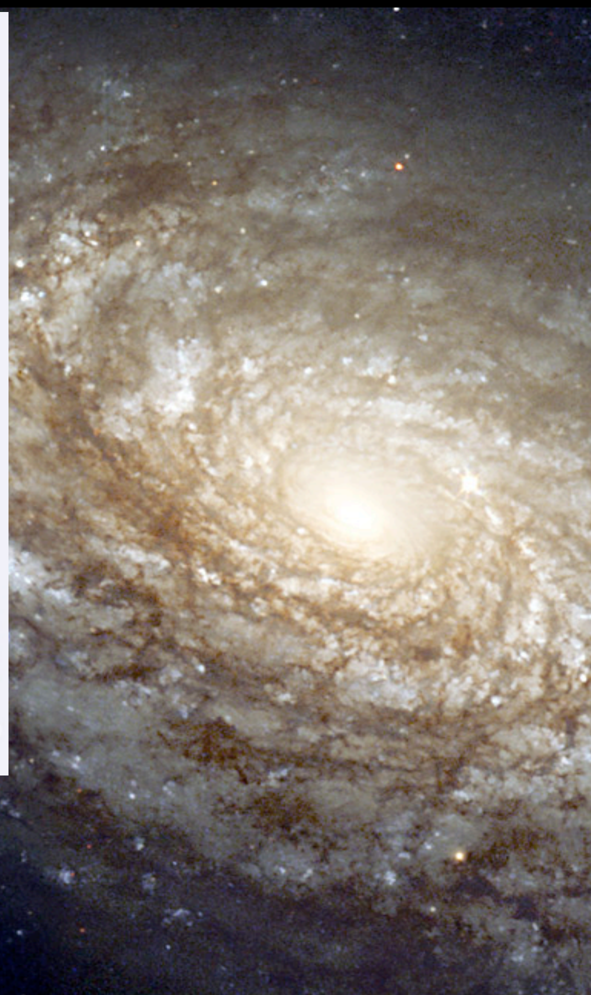
Paul Dirac's View of History

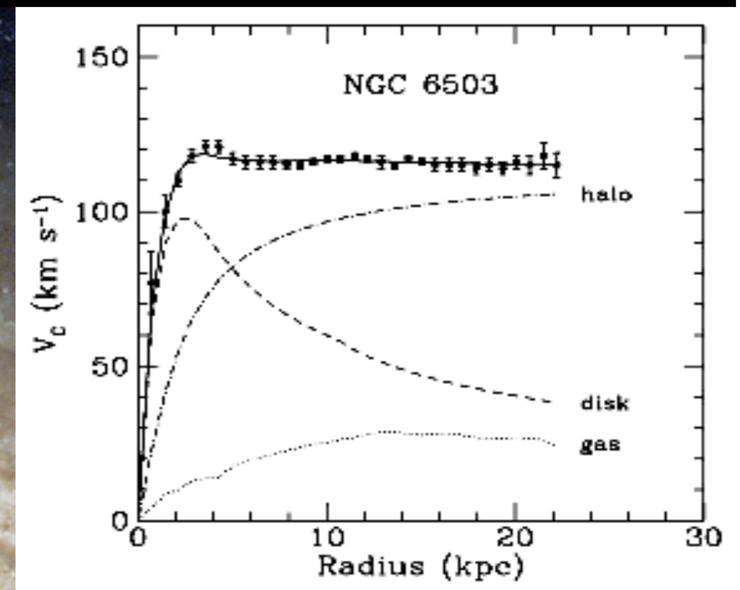
When I first thought of the idea I thought that this particle would have to have the same mass as the electron, because of the symmetry between positive and negative masses and energies which occurs all the way through this theory. But at that time the only elementary particles that were known were the electron and the proton. I didn't dare to postulate a new particle. The whole climate of opinion in those days was against postulating new particles, quite different from what it is now. So I published my work as a theory of electrons and protons, hoping that in some unexplained way the Coulomb interaction between the particles would lead to the big difference in mass between the electron and the proton.

Of course I was quite wrong there and the mathematicians soon pointed out that it was impossible to have such a dissymmetry between the positive and negative energy states. It was Weyl who first published a categorical statement that the new particle would have to have the same mass as the electron. The theory with equal masses was confirmed a little later by observation when the positron was discovered by Anderson.

What is the Dark Matter?



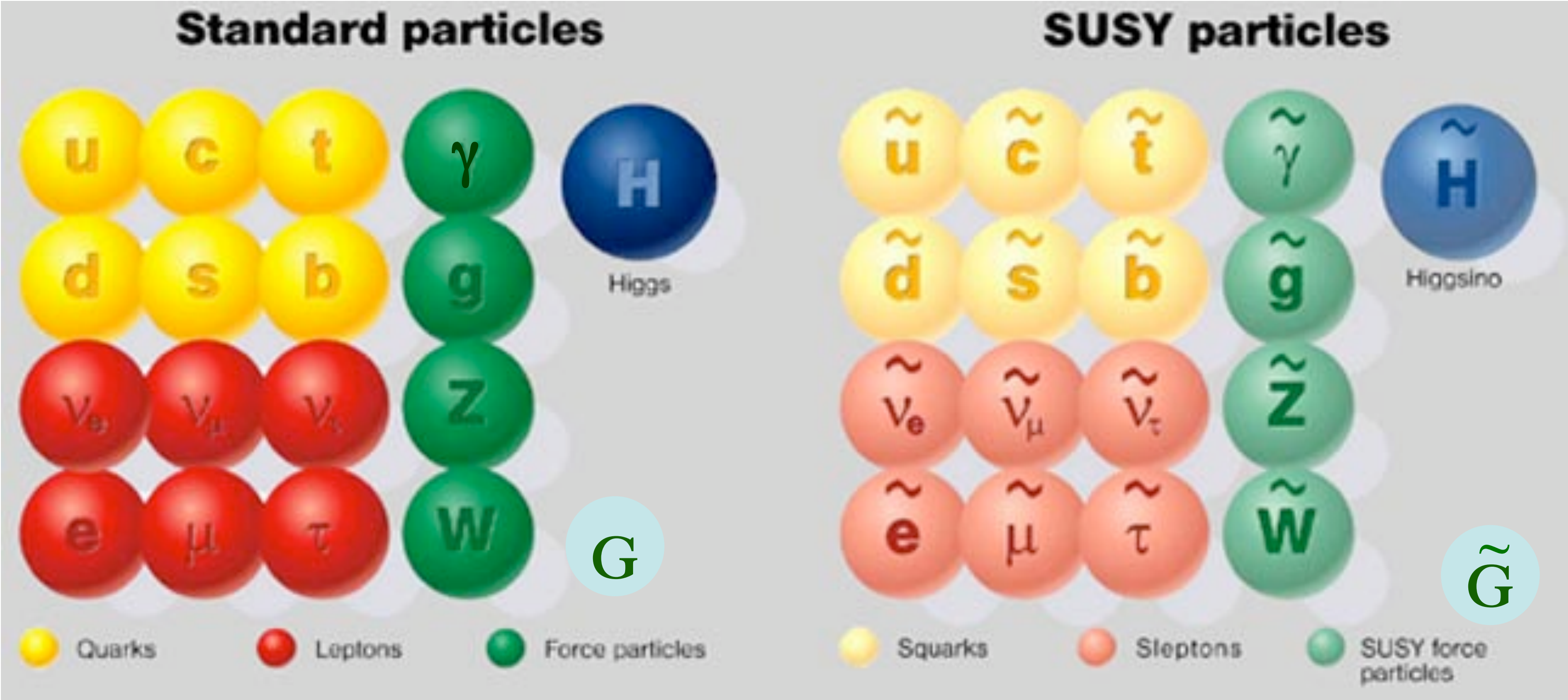




Standard Model only accounts for 20% of the matter of the Universe

$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

Supersymmetry (SUSY)

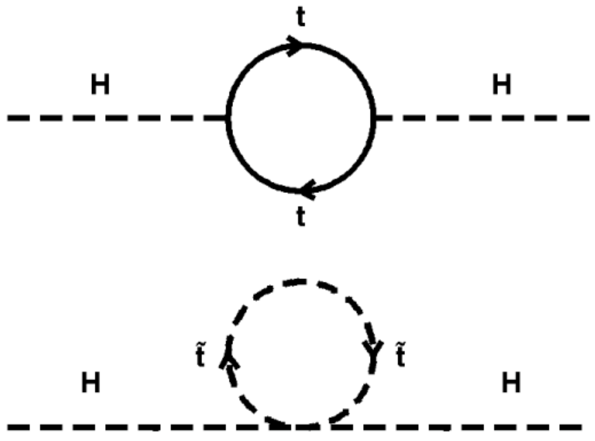


- SM particles habe supersymmetric partners:
  - Differ by 1/2 unit in spin
- No SUSY particles found as yet:
  - SUSY must be broken
  - breaking mechanism determines phenomenology

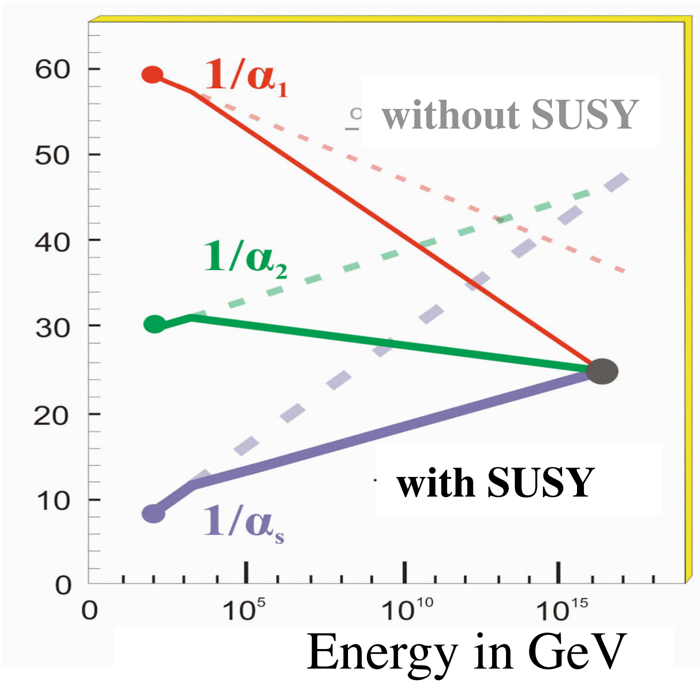
SUSY can solve some problems

- **No (or little) fine-tuning required**
  - Relies on stop mass being not too high

$$\Delta m^2_{\text{top}} + \Delta m^2_{\text{stop}} = -6\frac{h_t^2}{4\pi^2}(m_{\tilde{t}}^2 - m_t^2)\log\frac{1}{r_H^2 m_{\tilde{t}}^2}$$



- **Unifications of forces possible**
  - SUSY changes running of couplings
- **Dark matter candidate exists:**
  - The lightest neutral partner of the gauge bosons

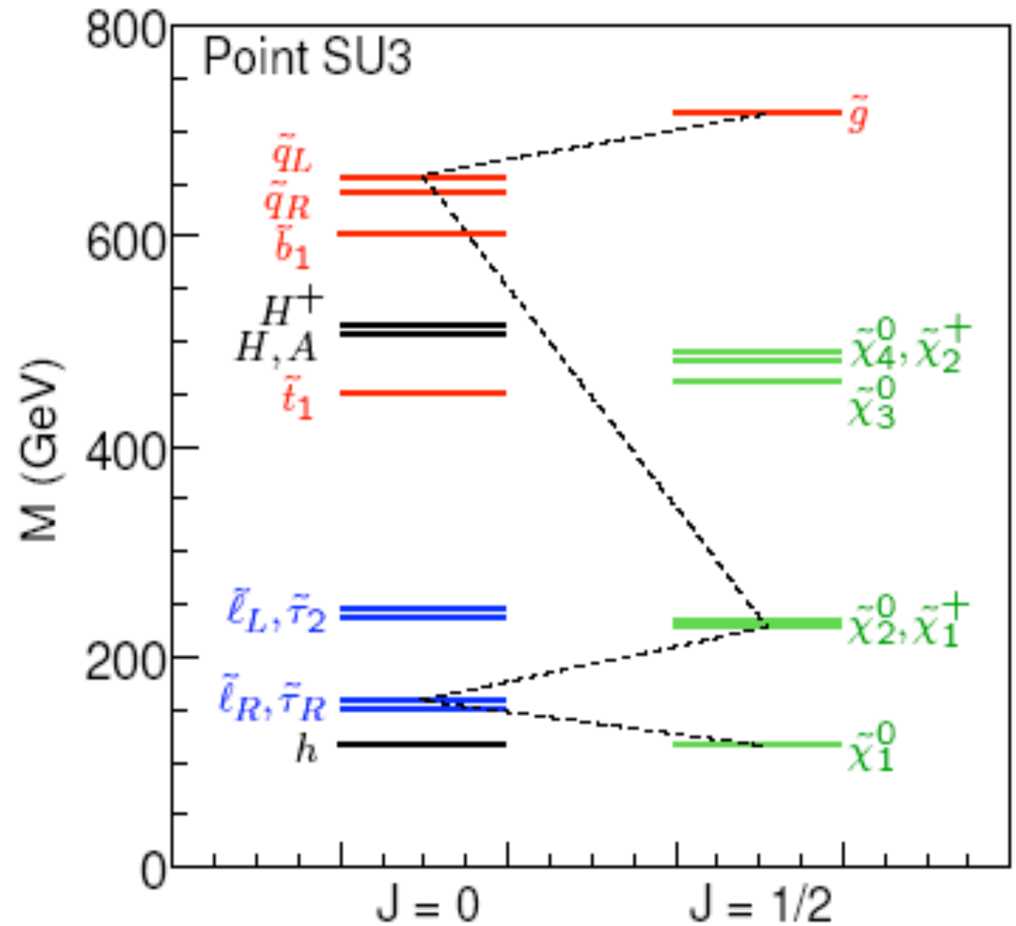


Mass of supersymmetric particles must not be too high (~1 TeV)

A Typical Sparticle Mass Spectrum

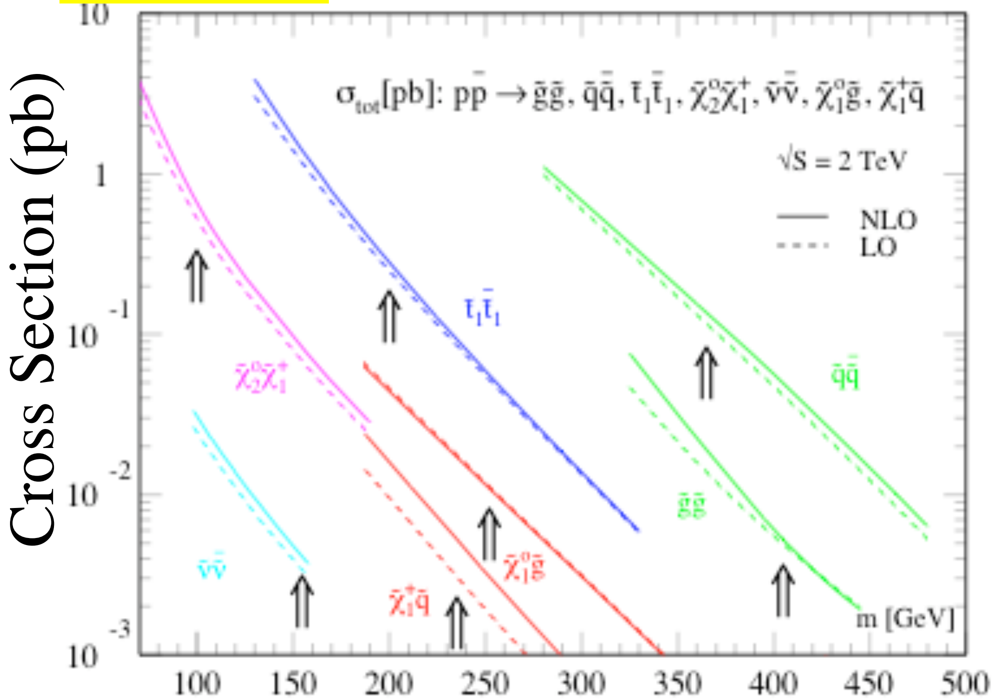
- 5 Higgs bosons
  - M_h<135 GeV/c^2
- Squarks and gluino heavy
  - Stop lightest
- Charginos + neutralinos lightish
  - Mixed states of W, Z, γ
  - Dark matter candidate: $\tilde{\chi}_1^0$
- Sleptons light

- Mass unification at e.g. 10^{16} GeV in some models
  - Common mass for all sferminons (m_0) and all gauginos ($m_{1/2}$)



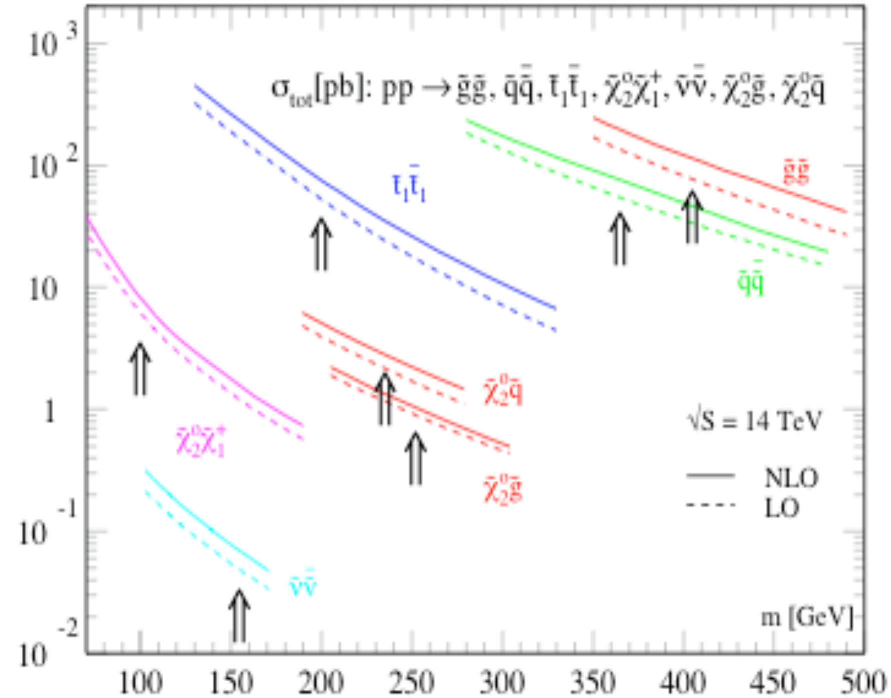
Sparticle Cross Sections

Tevatron



LHC

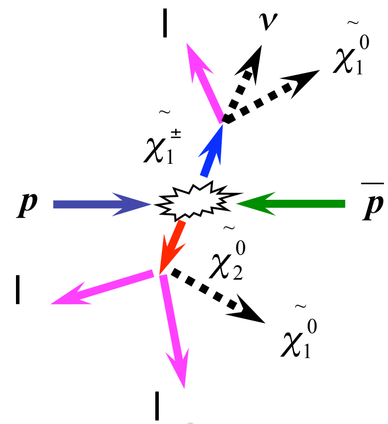
T. Plehn, PROSPINO

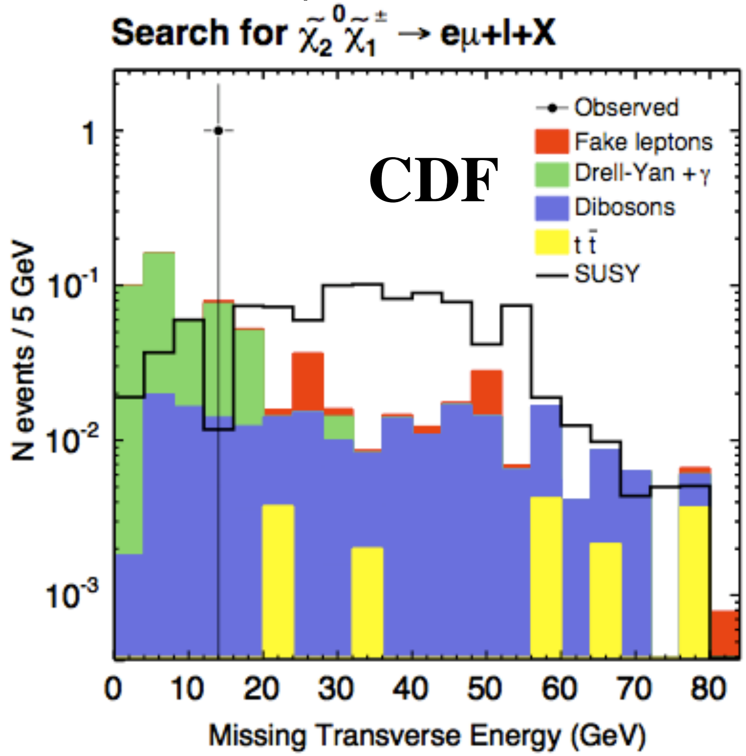


- **Most sensitive analyes at Tevatron:**
  - Chargino-neutralino production: 3 leptons + $\not{E}_T$
  - Squarks and gluinos: jets + $\not{E}_T$
- **Most sensitive at LHC:**
  - Squarks and gluinos: jets (+leptons) +$\not{E}_T$

3 leptons + $\not{E}_t$

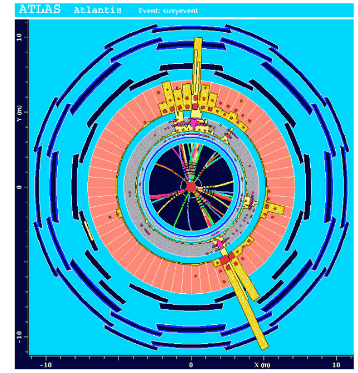
- **Produce Charginos and Neutralinos:**
  - Mixed states of SUSY partners of W, Z, photon and Higgs bosons
  - Directly probes their couplings
- **Limits of up to 140 GeV on chargino mass**
  - Very model-dependent though
  - The hard limit from LEP is 103.7 GeV
- **Not a discovery channel at early LHC**
  - But critical for understanding SUSY model



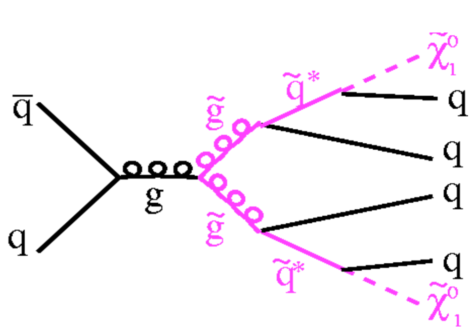


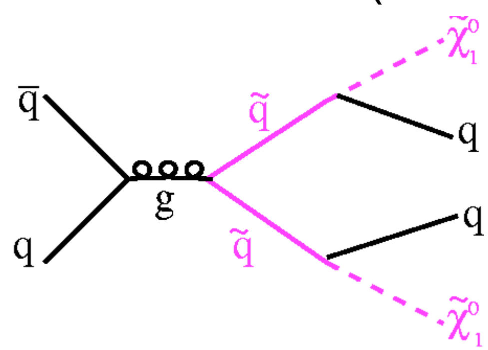
Phys. Rev. Lett. 99, 191806 (2007).

Squarks and Gluinos at the LHC

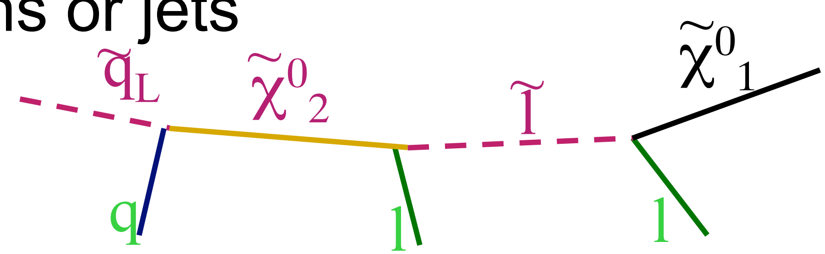


- Cross section nearly model-independent
  - for $m(\tilde{g})$=400 GeV: $\sigma_{LHC}(\tilde{g}\tilde{g})/\ \sigma_{Tevatron}(\tilde{g}\tilde{g}) \approx 20{,}000$
  - for $m(\tilde{q})$=400 GeV: $\sigma_{LHC}(\tilde{q}\tilde{q})/\ \sigma_{Tevatron}(\tilde{q}\tilde{q}) \approx 1{,}000$
    - Since there are a lot more gluons at the LHC (lower x)

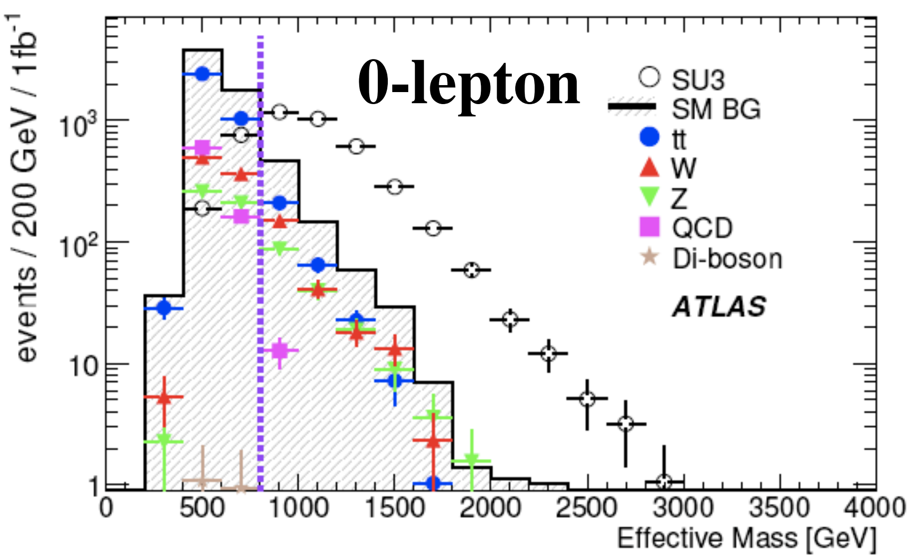


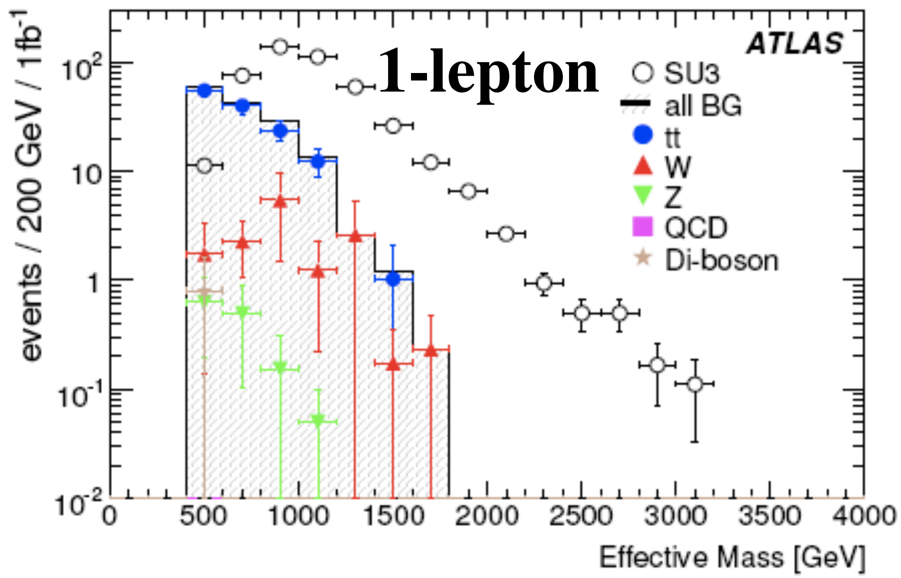


- At higher masses more phase space => decay in cascades
  - Results in additional leptons or jets
  - Very model-dependent

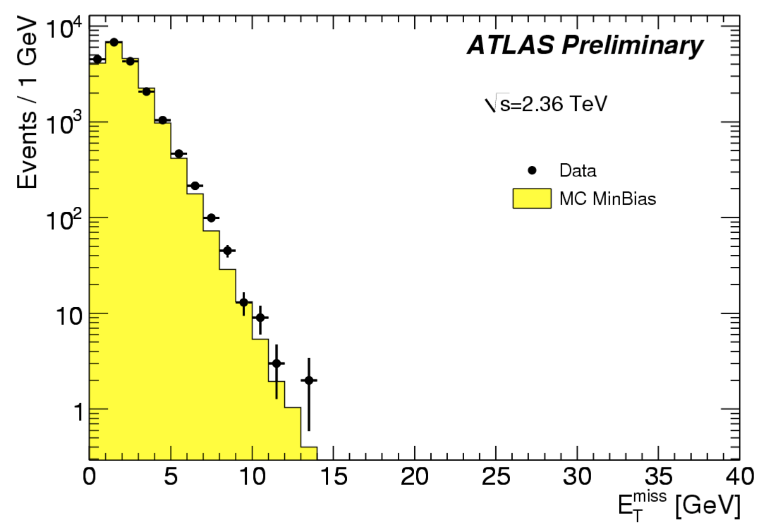


Search Analyses: 0, 1, 2.. leptons+jets

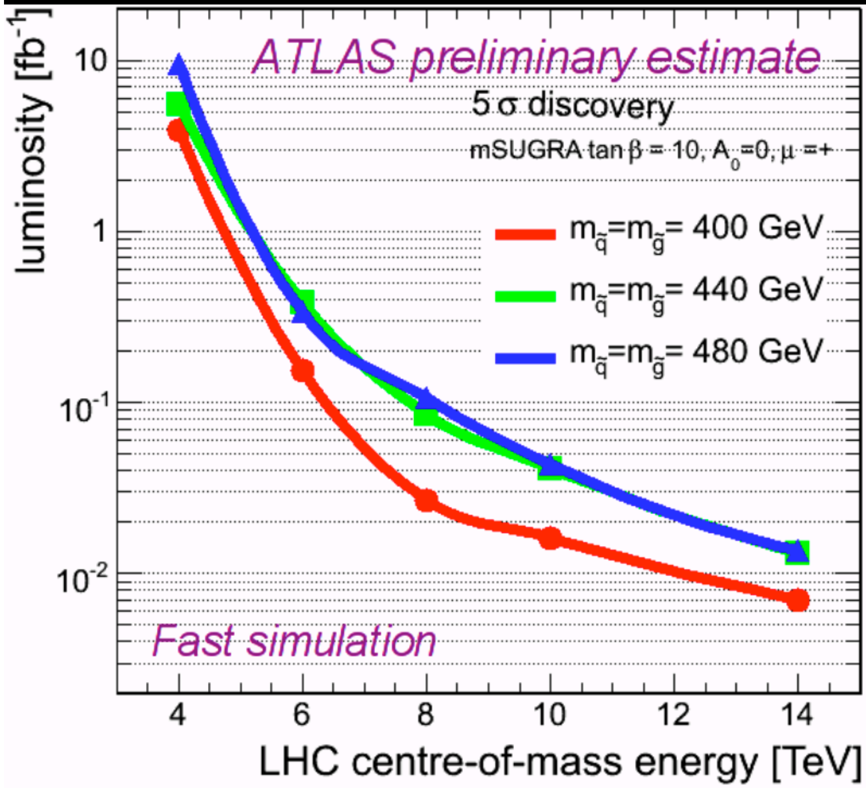


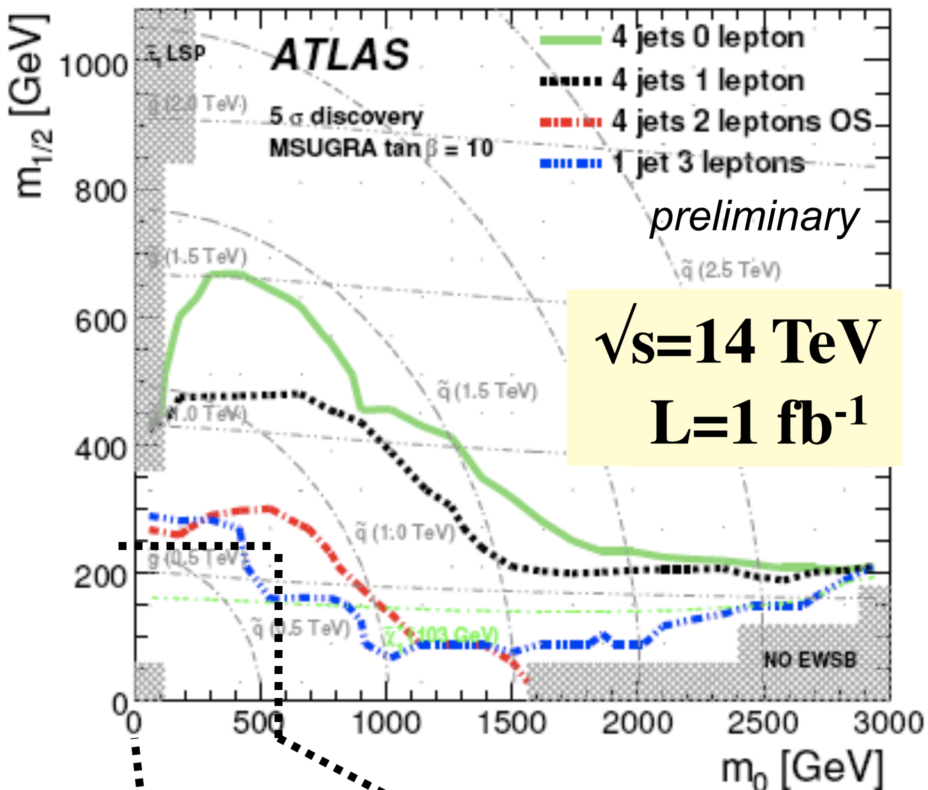


- Signal can appear in many search analyses simultaneously
  - Depends on model details
  - Important to do all of them
- Top is most severe background in general
- Missing E_T well understood in 2009 data

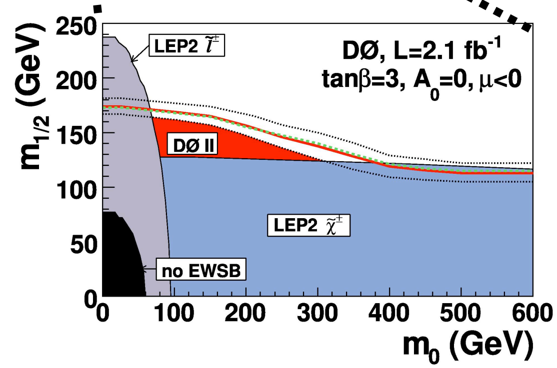


LHC SUSY Discovery Reach





- Current limits (Tevatron):
  - $m(\tilde{g})>300\text{-}400\ GeV/c^2$
  - LHC will surpass with ~0.1 fb^{-1}
- With 1 fb^{-1} at 14 TeV:
  - Sensitive to $m(\tilde{g})<0.5\text{-}1.5\ TeV/c^2$

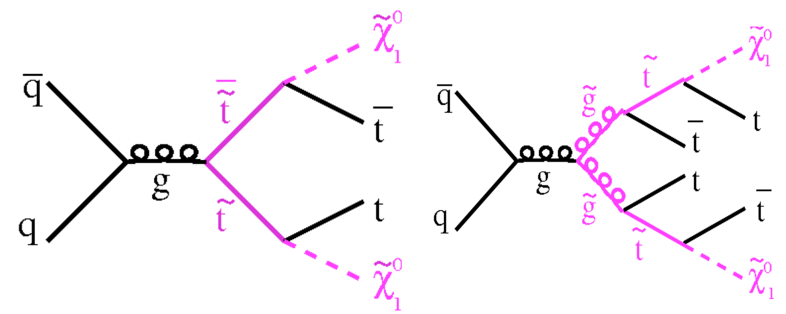


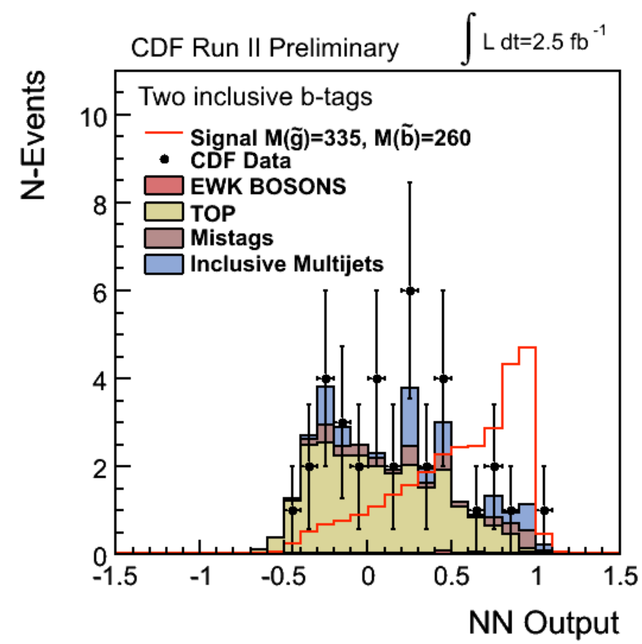
3rd generation Squarks

$$m^2_{\tilde{t}_{1,2}} = \frac{1}{2}(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R}) \mp \sqrt{(m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R})^2 + \underline{4m_t^2(A_t - \mu \tan\beta)^2}}$$

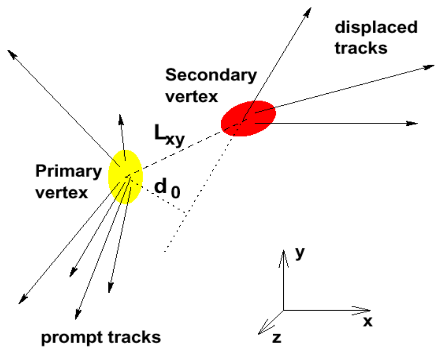
Baer et al. (1990), Hisoni et al. (2002), Tohari and Wells (2006), Acharya et al. (2009)

- 3rd generation is special:
  - Masses lower due to large SM mass
    - Particularly at high tanβ
- Spectacular signature
  - b-tagging critical
  - could dominate at LHC
    - Important to understand flavor content of any eventual signal
- Current constraints are about
  - $M(\tilde{b})>230$ GeV and $M(\tilde{t})>150$ GeV
    - Depending strongly on masses of neutralino and gluino

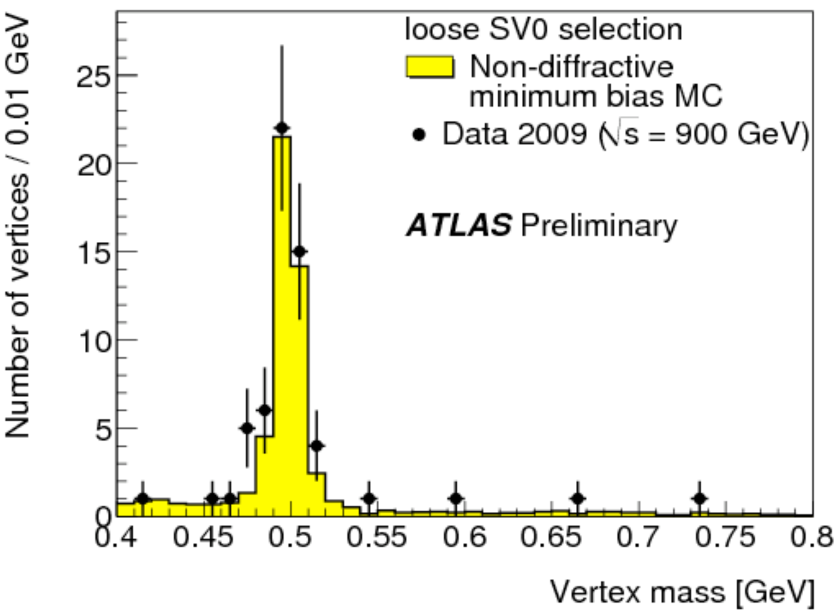




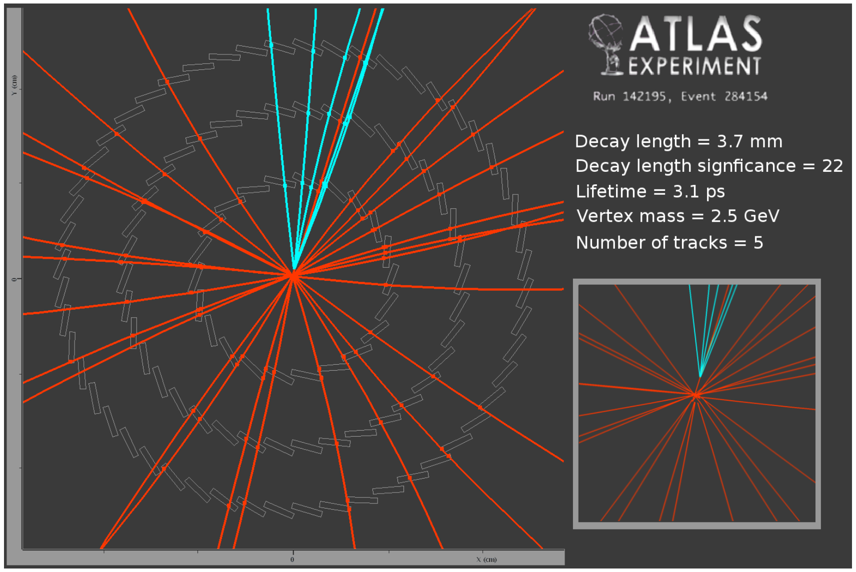
First B-tags in ATLAS



Decay distance of b:
cτ≈0.5 mm



- Vertex tags in 900 GeV data
  - Remove vetoes against K^0_s, Λ^0, material interactions
  - Good agreement between data and MC
- May have seen first b-jet in ATLAS



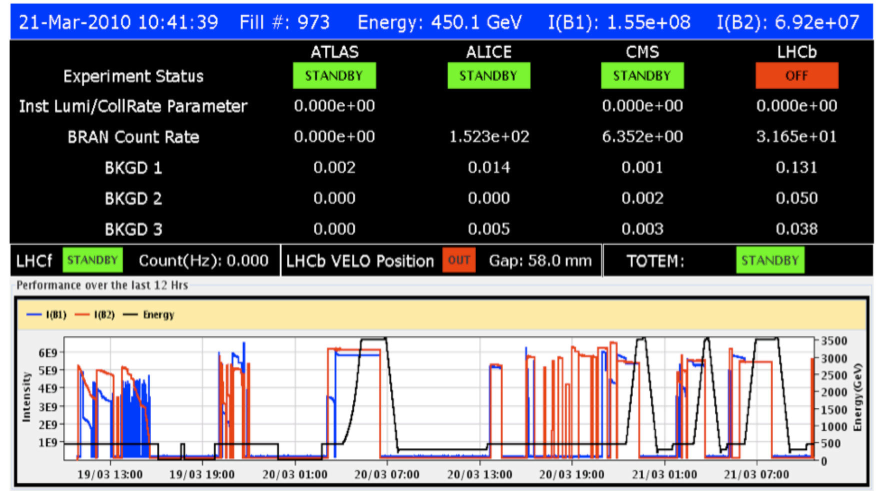
What Else?

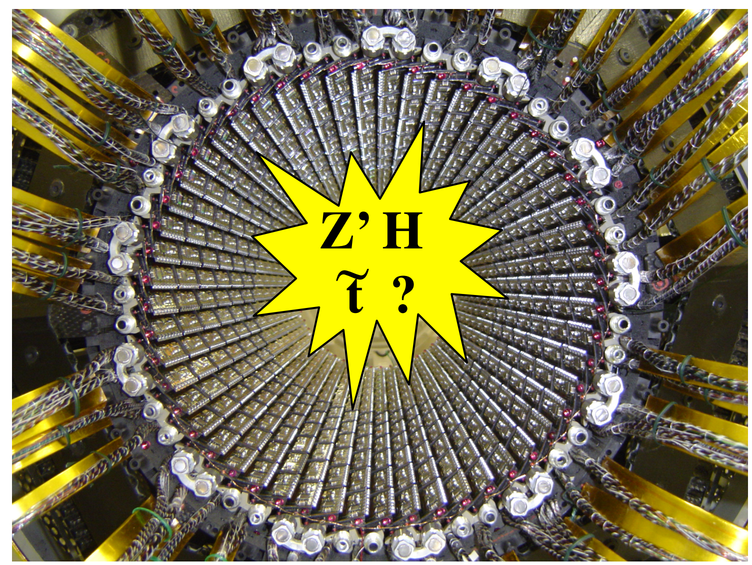
[Hitoshi Murayama]

Need to be open-minded for searches for new physics

Concluding Remarks

- **Tevatron has probed Standard Model in great depth**
  - Precision SM measurements
  - Direct searches
- **The LHC era has started!**
  - Detectors are operating well
- **Excellent Prospects for finding e.g.**
  - Higgs boson (or something else)
  - Supersymmetry
    - if it solves the hierarchy problem…
  - A surprise!
    - extra dimensions, new generations,...
- **Full LHC/sLHC and LC needed to understand underlying theory**



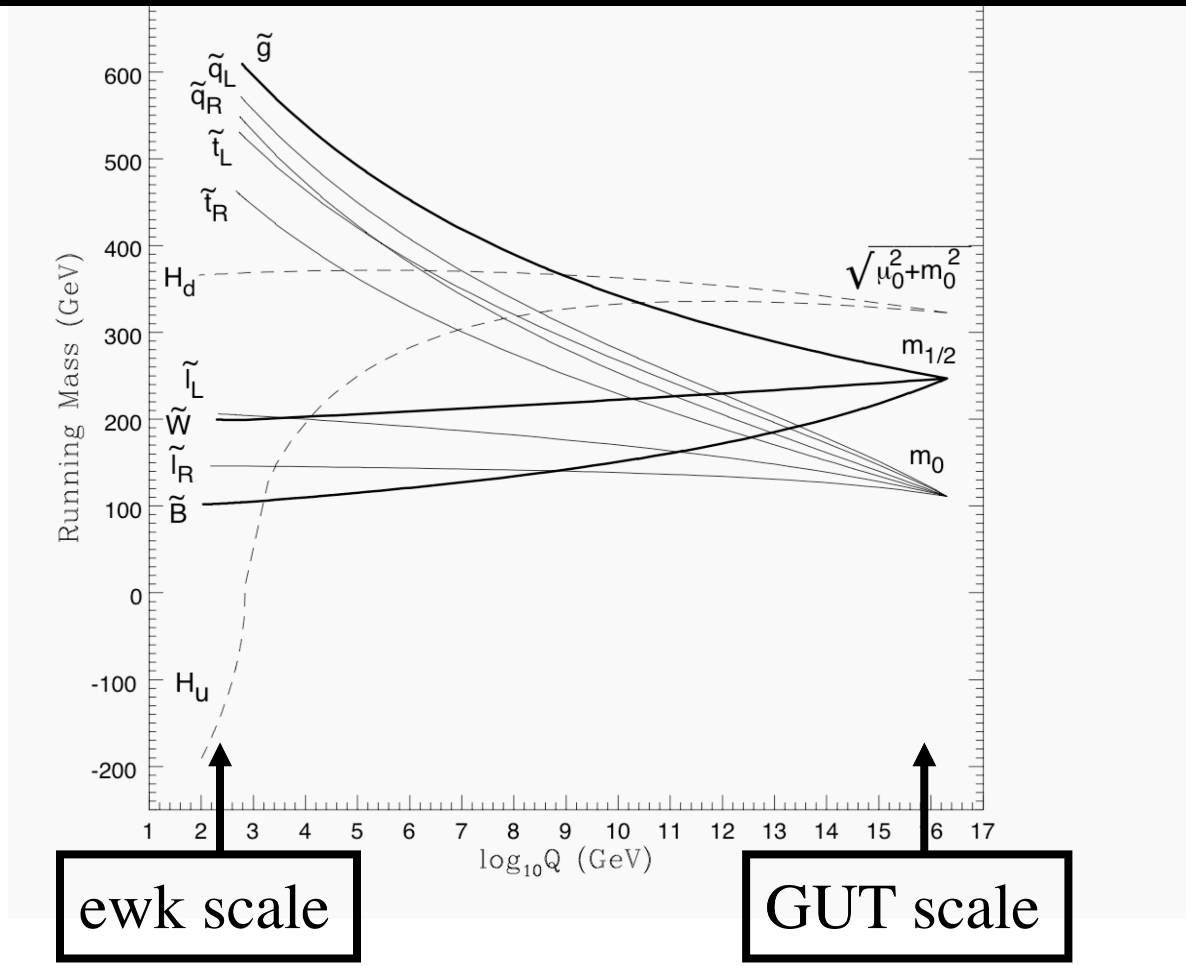


LHC Beam Parameters: 2010/2011

Step	Phase	N	N_b^{max}	N_{tot}/N_{tot}^{nom} [%]	E_{beam} [MJ]	L [$cm^{-2}s^{-1}$]
2/3	Beam commissioning – respecting safe beam limit	$2x10^{10}$	2	0.01	0.02	$3.6x10^{28}$
3	Pilot physics – squeeze to target values	$3x10^{10}$	43	0.4	0.7	$1.7x10^{30}$
4		$5x10^{10}$	43	0.7	1.2	$4.8x10^{30}$
5		$5x10^{10}$	156	2.4	4.4	$1.7x10^{31}$
5/6		$7x10^{10}$	156	3.3	6.1	$3.4x10^{31}$
7	Bring on crossing angle – truncated 50 ns.	$7x10^{10}$	144	3.1	5.7	$2.5x10^{31}$
8		$5x10^{10}$	288	4.4	8.1	$2.6x10^{31}$
8/9		$7x10^{10}$	432	9.3	17	$7.5x10^{31}$
9		$7x10^{10}$	796	17.1	31.2	$1.4x10^{32}$

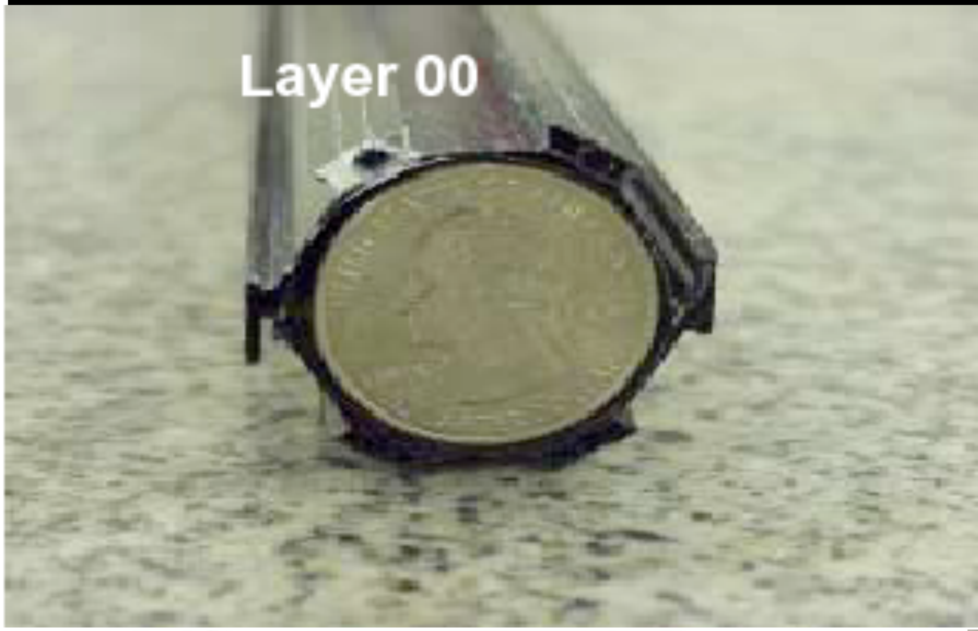
M. Giovanozzi, Evian, January/2010

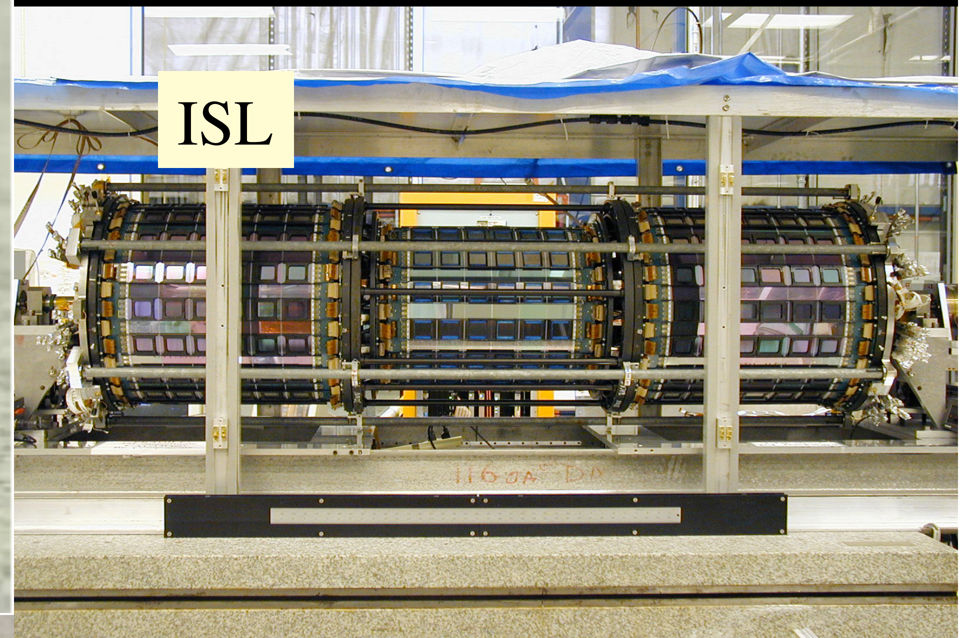
Mass Unification in mSUGRA

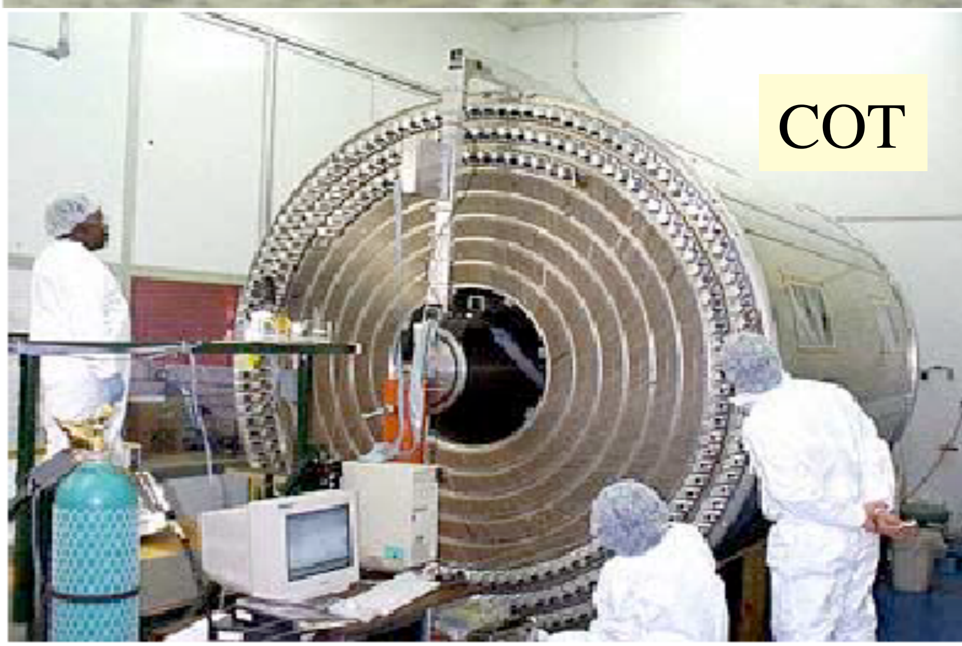


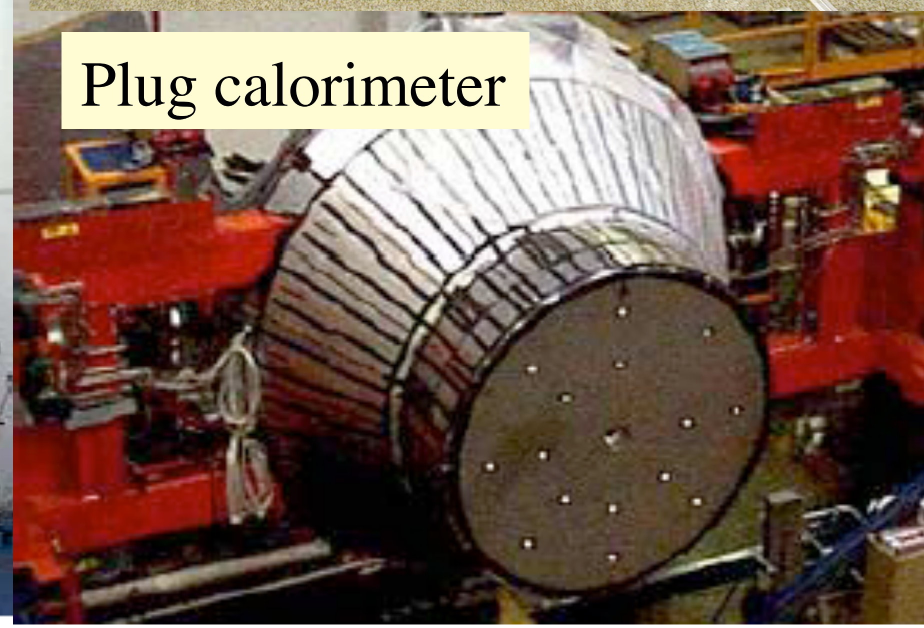
- Common masses at GUT scale: m_0 and $m_{1/2}$
  - Evolved via renormalization group equations to lower scales
  - Weakly coupling particles (sleptons, charginos, neutralions) are lightest

Some CDF Subdetectors

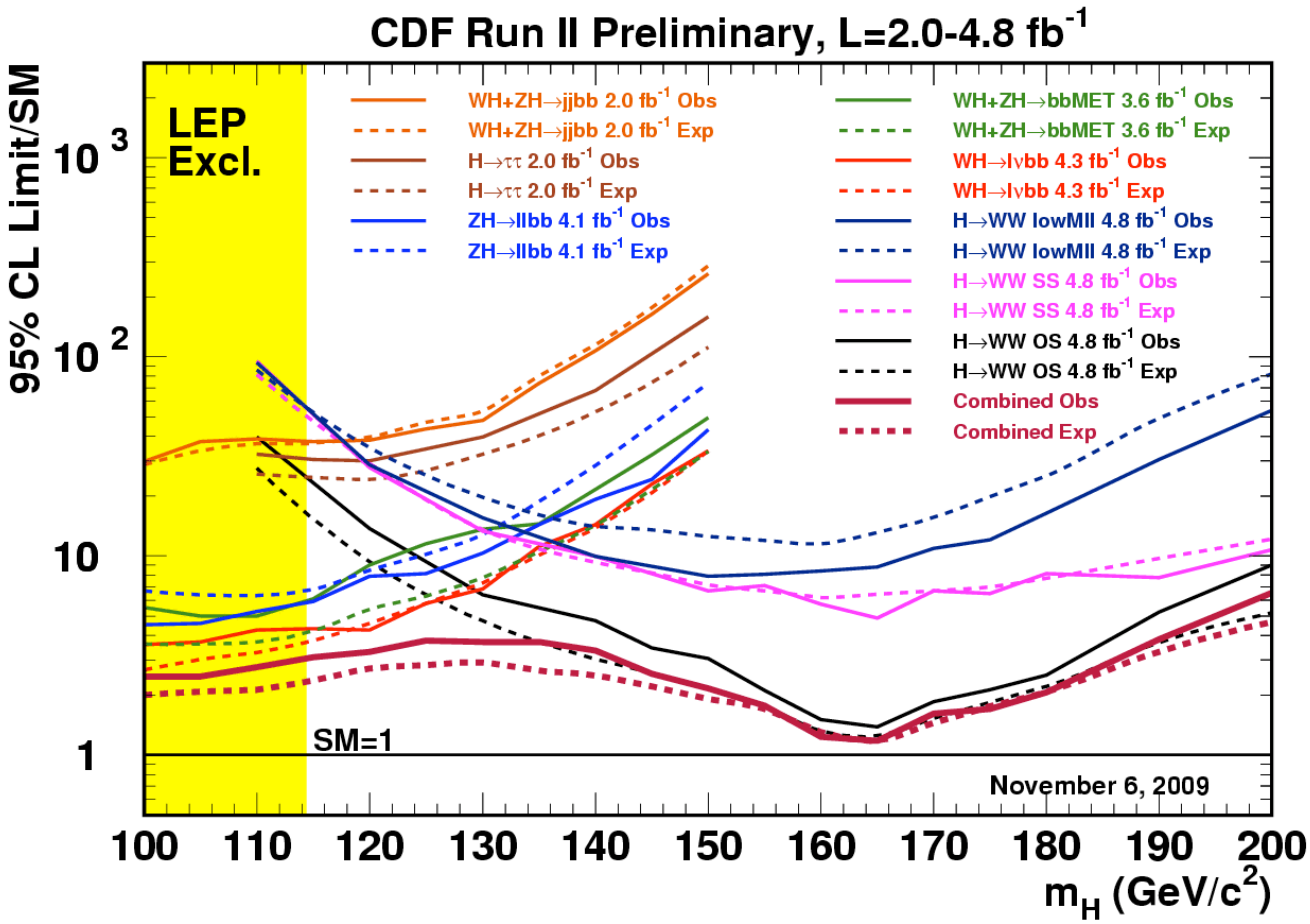








CDF Combined Higgs Result



- Combination of many analyses results
  - M_H>130 GeV/c^2: mostly constrained by WW channel
  - M_H<130 GeV/c^2: mostly constrained by WH and ZH analyses